THE DEVELOPMENT OF A NOVEL RANGE OF HIGH VOLTAGE FULL-RANGE FUSE-LINKS

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The University of Glamorgan in collaboration with B & S Fuses (now part of Bussmann Division, Cooper UK Limited)

Declaration

This dissertation has not, nor is being currently submitted for the award of any other degree or similar qualification.

Signed......Neil Davies......

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Abstract

Traditionally manufactured 'Back-Up' fuse-links have an area of uncertainty - zones where there is no certainty that these fuses will be able to successfully interrupt the current after melting of the fuse element has begun. Advances in fuse technology have led to a new category of HV fuse-link - the 'Full Range' fuse. 'Full Range' fuses do not have this area of uncertain operation, and are able to safely interrupt all currents that cause the fuse elements to melt.

The 'Fullran' range of HV full range fuse-links are a totally unique product and have many excellent features. However, a major drawback to the design were its unfavourable time/current operating characteristics. After introducing the various categories of HV fuse-link, this dissertation looks at the work carried out on the Fullran fuse-links as part of a Teaching Company Scheme (TCS) between the University of Glamorgan and B & S Fuses.

The dissertation will show how the unique range of Fullran HV fuse-links have been further developed, using a completely novel arrangement of fuse-element, to produce new commercially available designs that comply with both UK and international standards. Details will be given on the initial concept of the element arrangement and the first prototype fuse-links designed using a 'multi-element bridge configuration'. The dissertation will then show the complete development process of the new designs starting with laboratory testing of the original prototypes, to short-circuit testing of the first production designs, onto redesigns for improved performance and finally through to the certified designs.

Other areas which were covered by the TCS programme included the introduction of 'Fullran technology' into existing B & S Fuses products and an upgrade of the

company's quality and production procedures. This dissertation will show how the Fullran technology was introduced into a British Standards dimension fuse-link for use under oil and fully certified to IEC 282-1 for full-range performance. Details are also given on how production and quality procedures were upgraded to tie in with the company's drive for quality and accreditation to ISO 9002 for the manufacture of HV fuse-links.

Also included in the dissertation is a section on mathematical modelling of the Fullran fuse using finite element analysis. This work details the investigation into using the ANSYS finite element analysis software to produce a model of a Fullran fuse-link.

Contents

Figure List

1. Introduction

This MPhil report describes the work undertaken during a Teaching Company Programme between the Department of Electronics & I.T. at the University of Glamorgan and B & S Fuses Limited. The programme was completed over a two year period between April 1993 and April 1995.

1.1 The Teaching Company Scheme (TCS)

The Teaching Company Scheme uses government funds to support partnerships between companies and universities. 'Associates' are recruited to carry out commercially important and exacting development projects which are supervised by senior company personnel and experts from the collaborating university. TCS provides a structured professional development over a two year period, encouraging personal development in managerial, technical and business skills through the supported completion of these high profile strategically important projects.

1.2 B & S Fuses Limited

B & S Fuses Limited (originally known as Bouckley and Sawyer Fuses) was established in Birmingham in 1974 as a division of Bouckley and Sawyer Limited. In 1976 the fuse division broke away to form the new company B & S Fuses Limited and moved to Bridgend, South Wales. The company's activities were increased during the 1980's with the acquisition of several smaller private companies that specialised in the manufacture of products complimentary to high voltage fuses. In 1991 the company group was restructured and incorporated as Mortimer Holdings Limited, a group holding company.

During the time of the Teaching Company Programme (March 1994), B & S Fuses Limited was acquired by the $6 billion Cooper Industries group who are a world leader in power fuses and associated products. The B & S business became part of Cooper's Bussmann Division and was managed separately within Bussmann's U.K. business segment as a subsidiary of Cooper (UK) Limited.

The Teaching Company Scheme between B & S Fuses and the University of Glamorgan had the full support of Bussmann and continued to its normal conclusion in April 1995, with the same management team.

1.3 The Objectives of the Teaching Company Programme

B & S Fuses has been manufacturing a wide range of High Voltage (HV) current limiting fuses since 1974. These fuses are generally of the 'back-up' design for short circuit protection of electrical distribution systems. They have a limited performance under low fault / overload conditions and are normally used in Fuse-Switch equipment which provide three-phase mechanical switching under low current operation. These fuses are certified to British and International standards and are approved by the British Electrical Supply Industry.

More than 75 % of B & S products were sold in export markets influenced by British Standards. These included Australia, New-Zealand, Canada, South Africa and Malaysia and a small percentage into western Europe for use in distribution equipment produced in the U.K.

B & S Fuses recognised that if it were to increase it's share of the European and other overseas markets, it would be necessary to enhance its research and development profile and develop a new range of high-voltage fuses to the latest IEC standards using 'state of the art' technology in design and production. One way in which the company decided to go about achieving this target was through the introduction of a Teaching Company Programme.

At the time of commencement of the Teaching Company Programme, B & S Fuses had identified its key objectives and strategies as follows:

1. to hold and, where possible, improve its market share for high-voltage fuses.
2. to maintain its reputation as a manufacturer of high quality, state of the art, electrical products.
3. to develop a new generation of products to enable the company to compete in new markets, particularly export.
4. to obtain full quality approval to BS5750.
5. to develop and train key skill resources.

The Teaching Company Programme was conceived primarily to address objectives 2, 3 and 5. The specific overall objectives of the programme being:

a. to increase the company's knowledge and skills in so called 'Fullran' technology using thick-film printing and electroplating techniques (see Chapters 2 & 3).

b. to introduce new more sophisticated plant and equipment for improved production efficiency and to release existing plant for product development.

c. to fully investigate the operating characteristics of the 'Fullran' fuse design using mathematical modelling and other simulation techniques.

d. to incorporate this technology in other B & S products to meet new technical standards and thereby consolidate and improve market share in the Electrical Supply Industry.

e. to improve the company's product quality by establishing new procedures for assessing and improving the new manufacturing processes.

f. to enable the Associate to gain engineering and management skills to meet the future needs of B & S Fuses.

g. to enable the Associate to gain experience in working in a multi-discipline company producing high quality electrical products.

The programme was successfully completed, and the outcomes of the programme form the basis of this dissertation. The remainder of this first chapter will provide an introduction to the subject of HV fuse-links showing how they are defined and highlighting their operating characteristics. For quick reference, a glossary of terms is also provided at the back of the thesis.

Chapter 2 will introduce and define full-range fuses and show different design methods used to make full-range fuses. This chapter will also introduce the Fullran technology that B & S Fuses adopted from Holec Systemen of the Netherlands.

Chapter 3 will concentrate on the construction and manufacture of the Fullran type fuse-links and how the manufacturing and quality objectives of the Teaching Company Programme were addressed. Further details on quality issues that were dealt with during the programme are also given in Appendix A.

Chapter 4 will provide an overview of the traditional application of HV fuses in the UK and introduce some new concepts and trends in system protection. This chapter will basically give the reasons why the development of the Fullran fuse was considered such a high priority by B & S Fuses.

Chapter 5 will explain the development work carried out, through the Teaching Company Programme, on the Fullran full-range fuse-links concentrating on the 12 kV 6.3 - 40 A range. The chapter provides details on how a new type of fuse element design was used to develop the now commercially available modified Fullran fuses.

Chapter 6 will illustrate the development work carried out on the remainder of the 12 kV Fullran fuse range, that is the 50 - 80 A range, from initial development designs through to the modified designs currently being produced.

Chapter 7 will consider mathematical modelling of pre-arcing fuse operation for the Fullran fuses using finite element analysis techniques and in particular the use of the ANSYS software package.

Chapter 8 will review the considerable success of the Teaching Company Programme and the specific achievements with regard to the development of the Fullran design to meet both UK and International standards in terms of operating characteristics.

Included in the Appendices of the dissertation are details of a range of British Standard 2½" Oil Fuses which were developed and certified with full range performance. This work whilst not the main focus of the two year project, was a part of the teaching company programme in that it dealt with transferring the Fullran technology into existing B & S Fuses designs.

1.4 Introduction to Fuses

As electrical power technology throughout the world has progressed it has become possible to design and construct economic and reliable power systems which are capable of satisfying the continuing growth in the demand for electrical energy. Advances in the design of primary plant such as transformers, generators and switchgear has necessarily forced progress in the design and development of power system protection and control. Indeed, progress in the fields of protection and control is a necessity for the efficient operation and continuing development of power supply systems as a whole. [1]

Fuses and in particular h.b.c. (high breaking capacity) fuses are in vast and wide-spread use throughout the world, occupying an almost indispensable role in the protection of electrical systems. Fuses perform two basic functions:

a. *The passive function of carrying current during normal conditions in the circuit.* The passive function requires that the fuse should be able to carry normal load currents and even transient overloads for a service life of 20 years or more, without any change of state that might affect its electrical performance. This property of 'non-deterioration' implies that the fusible element is both thermally and chemically compatible with the ambient media.

b. *The active function of interrupting overcurrents during fault clearance.* The active function requires that a fuse should respond thermally to overcurrents by melting and subsequently interrupting the circuit. The melting of a fusible element is followed by arcing, a manifestation of circuit energy which in power circuits can be very high, and the magnitude and duration of which is a function of the circuit. Successful fault interruption implies that the arcing is properly and wholly contained within the fuse cartridge: this capability is the breaking or rupturing capacity. Inadequate breaking capacity can result in disastrous damage and explosion in high-energy circuits. [2]

An equally important property of an h.b.c. fuse is concerned with its ability to limit fault energy, i.e. to melt and quench the arc long before the fault current can rise to the 'prospective' values which the circuit is capable of producing under fault conditions. This property requires considerable sophistication in fusible element design and involves complicated shaping of the elements quite apart from the choice of the basic material. A high degree of energy limitation is achievable with most well designed h.b.c. fuses. [3]

1.5 Characteristic Properties of High Voltage Fuse-Links

Definition of a Fuse-link

A fuse-link is a device comprising a fuse element or several fuse elements connected in parallel enclosed in a cartridge, usually filled with an arc-extinguishing medium and connected to terminations, the fuse-link is the part of a fuse which requires replacing after the fuse has operated. [4]

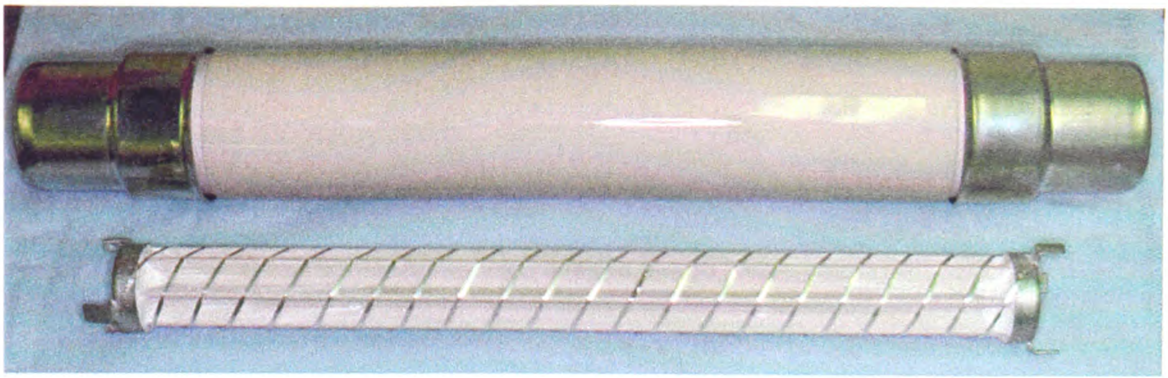


Figure 1 Photograph of a traditional element assembly and a finished fuse-link

1.5.1 Current Rating

The rated current of a fuse-link is stated as the rms symmetrical value. Under standard conditions of use the fuse will carry this current indefinitely. When selecting fuse-links for service a number of factors need to be taken into consideration and the rated current of the fuse-link is usually considerably higher than the normal service current.

Fuse manufacturers assign ratings to fuse-links based on a number of determining factors.

One factor is the temperature rise of the fuse-link contacts, determined at the temperature rise test as specified in IEC 282-1. [5]

The effect of placing the fuse-link in a location which is hot or thermally isolated or close to other fuse-links, for example, two other fuse-links of a three-phase set will also have an adverse effect on the operating temperature and derating of the fuse may be necessary. [6]

Manufacturers will also often determine the rated current based upon the need to ensure an adequate margin against deterioration of the fuse elements.

Manufacturers will also often determine the rated current based upon the need to ensure an adequate margin against deterioration of the fuse elements.

In order to avoid too many ratings, the preferred ratings of fuse-links are chosen from the R10 series. This series consists of 10 equal logarithmic steps in each decade (often rounded up to give whole numbers). The series from 6.3 A to 63 A is thus as follows :

6.3 - 8 - 10 - 12.5 - 16 - 20 - 25 - 31.5 - 40 - 50 - 63

It can be seen that each rated current is approximately 1.25 times the next lower rated current. For special applications other values of rating may be used.

Incorrect selection of rated current of a fuse-link for a given application could result in deterioration of fuse-link elements, contacts and of the enclosure. The factors that need to be regarded when selecting the current rating of the fuse-link are:

Any possible overload currents in the circuit; any transient effects related to switching equipment like transformers, motors or capacitors and co-ordination with other protective devices (if present). [5, 7]

1.5.2 Rated Voltage

The rated voltage of the fuse-link is the voltage for which the fuse has been designed. It cannot be assumed that fuses will operate correctly when used in a circuit of higher, or significantly lower, voltage than the stated rated voltage.

When arcing is initiated in a fuse-link, there is a significant increase in the voltage across it. For current limitation to effectively occur in HV fuse-links, this increase in voltage must be high. To achieve this, ribbon elements are generally used which have the effect of introducing a large number of short arcs under a high fault current. If a fuse-link of too low a voltage rating is used it is unlikely to have a sufficient length of fuse element to produce enough small arcs to extinguish the current. Therefore, if a fuse-link of too low a voltage rating is used would be likely to continue to arc excessively without limiting the current and it will probably explode.

Conversely, if a fuse-link of too high a voltage rating is used (which would therefore have longer fuse elements), the number of small arcs produced under a high fault current would result in too high a voltage developing across the fuse-link and the rate of change of current could be so large that excessive voltages may be induced in inductive components of the circuit [6]. Upper limits for fuse-link voltages are quoted in standards and specifications.

1.5.3 Time / Current Characteristics

In general a current higher than the rated current is required to cause melting of the fuse element. At currents above this value the fuse will operate in a time which decreases with increasing current. The time/current characteristic is a graph showing the operating time as a function of current (usually with a tolerance in the order of ± 10 % on current).

It is normal to plot the time/current curves showing the relationship between rms symmetrical available current and pre-arcing (or melting) time. For melting times less than say 100 ms, the incidence of the switching angle in relation to the circuit constants can cause considerable scatter in the time/current points. One method of overcoming this dispersal in melting times is to use the concept of 'virtual time'. [7]

Virtual Time is defined as 'the time for which a steady current equal to the prospective current would have to flow in a fuse to produce the same quantity of energy as would be produced if the actual current during the period of operation considered flowed in the fuse for the actual period'.

This time t_V is arrived at by dividing the pre-arcing Joule integral by the square value of the prospective current, i.e.

$$t_v = \int \frac{i^2}{I_p^{\;2}} dt$$

in which I_p is the prospective current and t_v is the virtual time of the period of operation under consideration.

For melting times greater than 100 ms the virtual time is practically equal to the actual melting time as the arcing time is usually negligible compared to the pre-arcing time. [8]

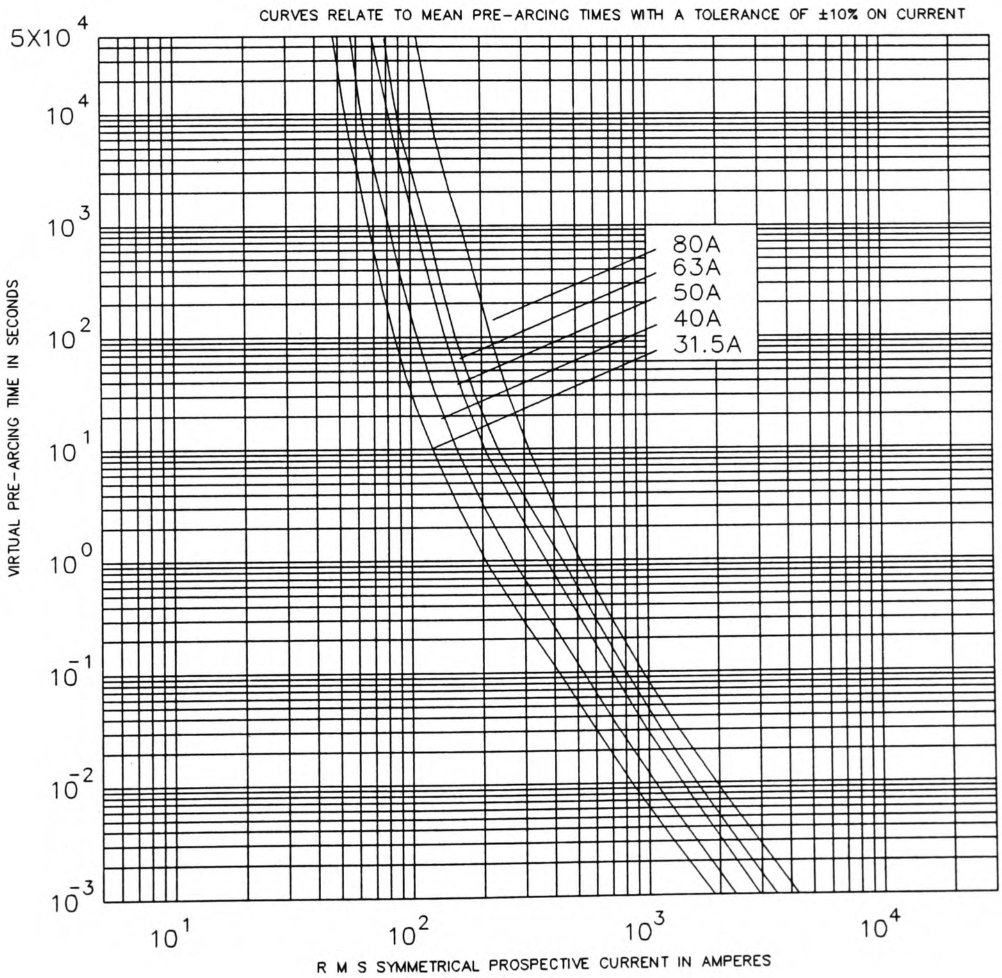


Figure 2 A typical time/current characteristic

1.5.4 Joule Integral (I^2t)

The Joule integral, otherwise known as the I^2t, (as mentioned in the calculation of virtual time) is a valuable characteristic property of a given fuse-link. It establishes a limit to the thermal stress on the protected circuit caused by the pulse of current let through by the fuse (when it operates on a fault current which causes the fuse to operate in a relatively short time). The I^2t is a rationalisation of the quantity $\int i^2 dt$ which is proportional to the energy let-through by a fuse during operation. The term I^2t is often used in American specifications and is referred to as 'let-thru'.

There are two kinds of I^2t shown in fuse literature, the pre-arcing I^2t, which covers the period up to the commencement of arcing when the fuse operates, and the total operating I^2t, which covers the whole operating period up to the final disconnection of the current by the fuse. If a pulse of current less than the pre-arcing I^2t is passed through the fuse, it will not 'blow'.

The I^2t characteristic is a curve or chart showing values of pre-arcing and total operating let through energies as a function of prospective current. A typical example of the characteristic is shown in figure 3.

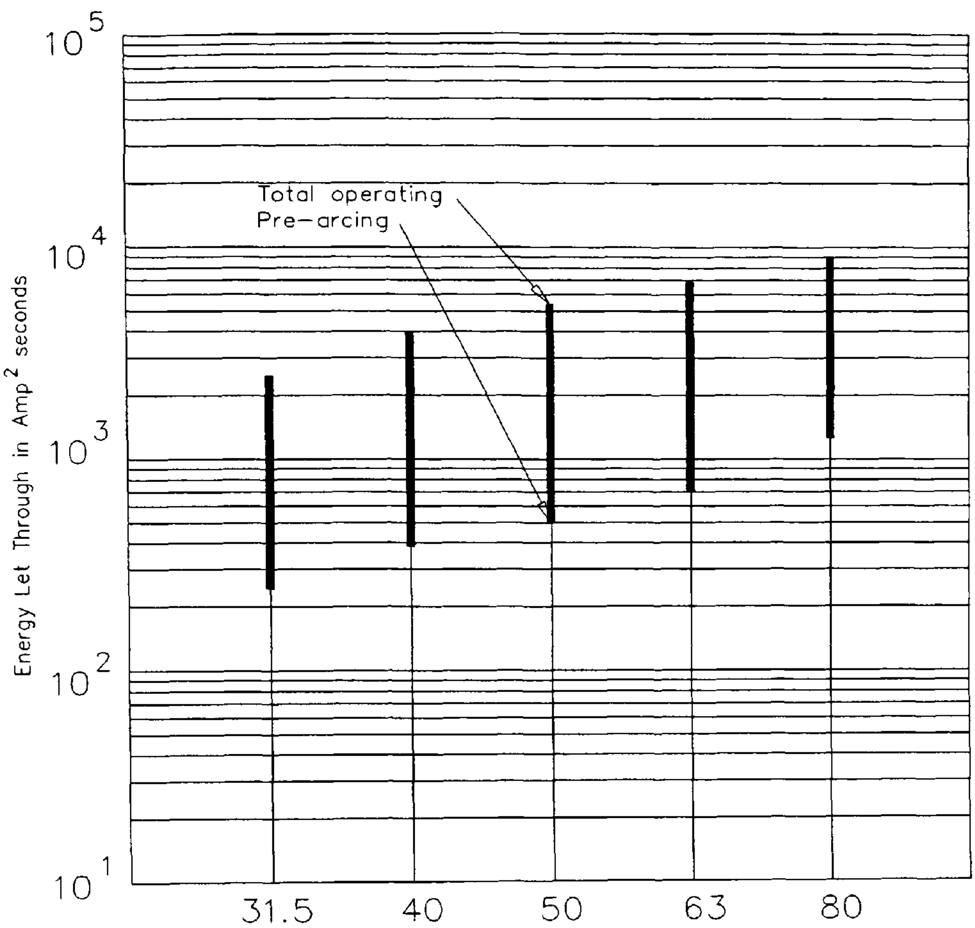


Figure 3 Variation of I^2t with current rating, showing maximum and minimum values of I^2t

1.5.5 Cut-off Characteristics

As explained earlier an important property of h.b.c. fuse-links is concerned with the ability to limit fault energy, that is, to melt and quench the arc long before the fault current can rise to the 'prospective' values which the circuit is capable of producing under fault conditions.

The maximum peak value that the current is limited to is referred to as the cut-off current. In the case of high prospective currents this cut-off current is far below the peak of the prospective current. The quicker the current is cut off, the higher may be the transient voltage peak (overvoltage) developed across the fuse. [6]

The cut-off characteristic is a curve detailing the cut off current as a function of prospective current, cut off current being the maximum instantaneous value of current let through by the fuse link during operation. An example of a typical cut-off characteristic is shown in figure 4.

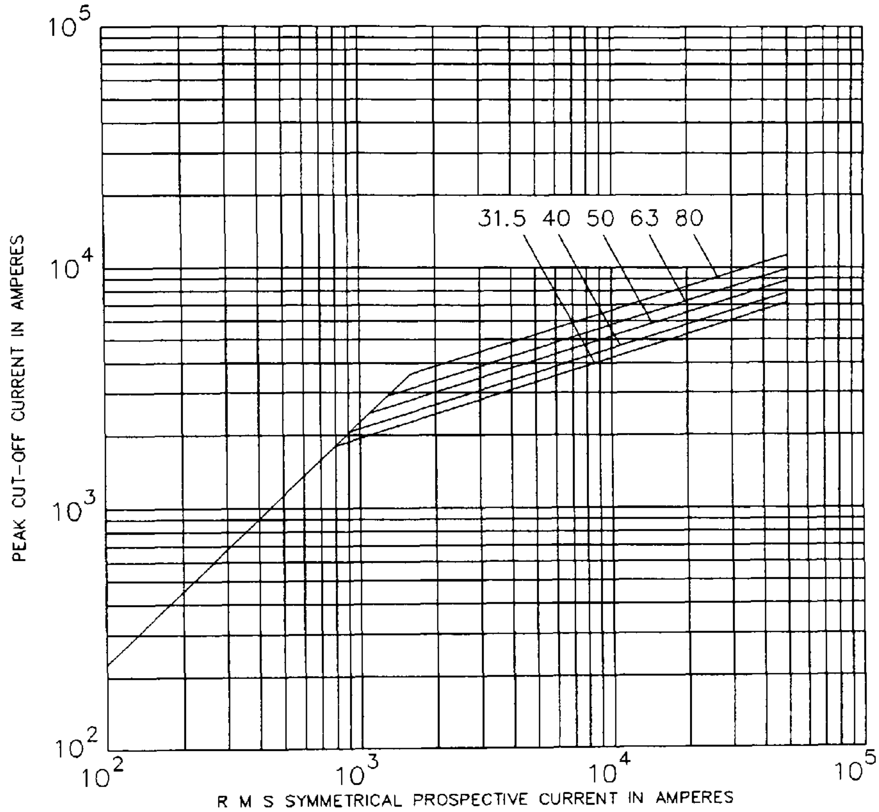


Figure 4 Typical cut off characteristic

1.6 Traditional Fuse-Link Designs

Traditionally there have been two types of High Voltage fuses used for the protection of distribution systems - current limiting, high breaking capacity (h.b.c.) fuses and non current limiting expulsion fuses. There are advantages and disadvantages to both types of fuse:

1.6.1 Current Limiting, h.b.c. Fuses

High breaking capacity (h.b.c.) fuses are of the cartridge type, contain one or more parallel connected fuse elements and are filled with compacted granular quartz (silica sand) with a high chemical purity. The advantages of h.b.c. fuses is the very high breaking capacity and the ability to limit the fault energy. Under high prospective fault currents (short-circuit conditions) h.b.c. fuses will melt and quench the arc long before the fault current can rise to the prospective values which the circuit is capable of developing under fault conditions.

The main disadvantage of the traditional h.b.c. fuse is the poor protection against small overcurrents.

Traditional current limiting fuse-links are divided into two classifications:

1.6.1.1 Back-Up Fuse

In the U.K. Electricity Supply Industry and countries influenced by UK practice e.g. Australia, India and the Middle and Far East, it has been general practice to use fuse-switch ring-main units in the electricity supply networks. The ring-main units are generally fitted with back-up fuses. A Back-Up fuse is a current-limiting fuse capable of breaking, under specified conditions of use and behaviour, all currents from the rated current down to the rated minimum breaking current.

In the U.K., the fuse-links must be provided with a strikers which will trip the switch instantaneously when one or more fuse-links operate. The tripping of the switch eliminates the possibility of trouble if the equipment is subjected to a fault current which is below the minimum breaking current of the fuse-link. It is only for fault currents below the minimum breaking current of the fuse-link that this external help is necessary. For currents greater than the minimum breaking capacity the fuse-link provides easy circuit interruption without the aid of the switch mechanism.

1.6.1.2 General-Purpose Fuse

A General-Purpose fuse is a current-limiting fuse capable of breaking, under specified conditions of use and behaviour, all currents from the rated breaking current down to the current that causes melting of the fuse-element in 1 hour or more. [5]

1.6.2 Expulsion Fuses

Expulsion fuses are installed in pole mounted fuse mounts and used in overhead line networks. Expulsion fuses usually contain a short element of tin or tinned copper wire in series with a flexible braid. The element assembly is mounted in a fuse carrier made from an organic material. There are various physical connection arrangements for expulsion fuses but in each case a fuse carrier is tilted from the vertical and held under tension by a spring in the fuse mount. When the fuse element melts during operation the tension is released which disengages a latch causing the fuse carrier to swing down by gravity. Expulsion fuses operate by preventing re-ignition after a current zero.

Expulsion fuses have excellent low overload breaking capacity - they can be set to trip on as little as 5 % overcurrent (e.g. 105 A for a 100 A rated fuse) and can have a time current characteristic which aligns closely with ideal requirements for low overload protection i.e. will hold rated current indefinitely but operate for a small percentage increase in current over the low overload operating region..

The disadvantages are the limited breaking capacity (typically limited to 150 MVA) and virtually no current / energy limiting properties. Expulsion fuses are also unsuitable for use indoors or in fusegear. [8]

1.7 Summary

To sum up these traditional fuse-link designs, it is fair to say, that whilst the various designs have become more advanced over the years leading to greater reliability and performance they still do not fulfil all the needs for the protection of distribution systems.

However, since the early 1980's a new type of fuse-link design has been available in the UK. These designs do not have the overload uncertainties of Back-Up or General Purpose fuses yet still have the current limiting properties.

These new fuse designs are designated ***'Full-Range'*** fuses.

The remainder of this dissertation will concentrate on full-range fuses, considering both their operational characteristics and the new design and production philosophies utilised in their manufacture.

2. Full Range Fuses

From discussions in the preceding chapter, it is apparent that traditional HV current limiting fuses have the disadvantage of not being able to break low overload currents. This has meant that striker tripped fuse-switch gear has been relied upon to provide safe clearance of low overload faults. [8]

However with the advent of 'Full Range' fuse-links this is no longer necessarily the case. This chapter will introduce the concepts and specifications of full range fuses and describe methods of how their design may be realised.

2.1 Full Range Fuses Defined

Definition IEC 282-1 : 1994

Full-Range Fuse

'A current-limiting fuse capable of breaking, under specified conditions of use and behaviour, all currents that cause melting of the fuse-element(s) up to its rated maximum breaking current'. [5]

This means that full range fuses have no area of uncertainty, they are able to successfully clear any fault current that causes the elements to melt and therefore do not have to rely upon a trip mechanism in a fuse-switch to clear low overload faults.

There is a continuing debate about the definition of a 'Full Range' fuse-link and the method of testing fuse-links for full range capabilities. [9]

When carrying out tests with long operating times, current is applied to the fuse-link using a low voltage source until all the elements have melted (the melting of the elements is detected by a sudden increase in the fuse resistance). As soon as all the elements have melted the low voltage source must be switched to a high voltage source such that current is interrupted for a time no longer than 0.2 seconds.

One of the two main suggestions for a definition and testing method is to define a full range fuse as : '*a current-limiting high voltage fuse capable of breaking under specified conditions of use and behaviour, all currents from the rated breaking current down to the smallest current which will melt the fuse element under normal service conditions*'. [10] The proposal for testing to this definition was a two-part test with the low voltage current set at the 1 hour melting current and the high voltage current set at a fixed percentage of the normal minimum melting current (e.g. 75 %). The intention of this being to simulate fuse performance with a significantly reduced minimum melting current (*Immc*) when installed in an enclosure with severely restricted ventilation.

Whilst this test would certainly cover the most onerous conditions that a fuse-link may see in practice, there may be a number of practical problems in setting parameters for this test and a number of points have to be taken into consideration.

1. The theoretical value of *Immc* is clearly defined in IEC 282-1 [5] but impossible to prove by one test as it must be interpolated from a series of tests at currents above and below *Immc* and therefore subject to a wide tolerance, possibly ± 10 % if selected from manufacturers published data.
2. The degree of shift in the time-current characteristic of a fuse-link mounted within a given enclosure will depend on the physical size of the fuse-link and the amount of heat generated during the pre-arcing period.
3. The value of *Immc* and its relationship to rated current (*In*) is a function of design and can vary considerably between different manufacturers products.

To nominate a test current as a fixed percentage of the normal *Immc* therefore does not appear consistent with the relationships given in (2) and (3) above. [11]

The alternative approach was again a two-part test with the low voltage current set at the 1 hour melting current but with the high voltage current set at the lower value of

In. This method, though more onerous, avoids the need to prove *Immc* as it uses the assigned value of *In* thereby making it a more practical option.

2.2 Testing for Full-Range Capabilities

Supporters of both testing practices can carry out their preferred tests by following the methods of testing laid out in the latest amendment of IEC 282-1 :1994. [5] A basic description of the full-range capability test is :

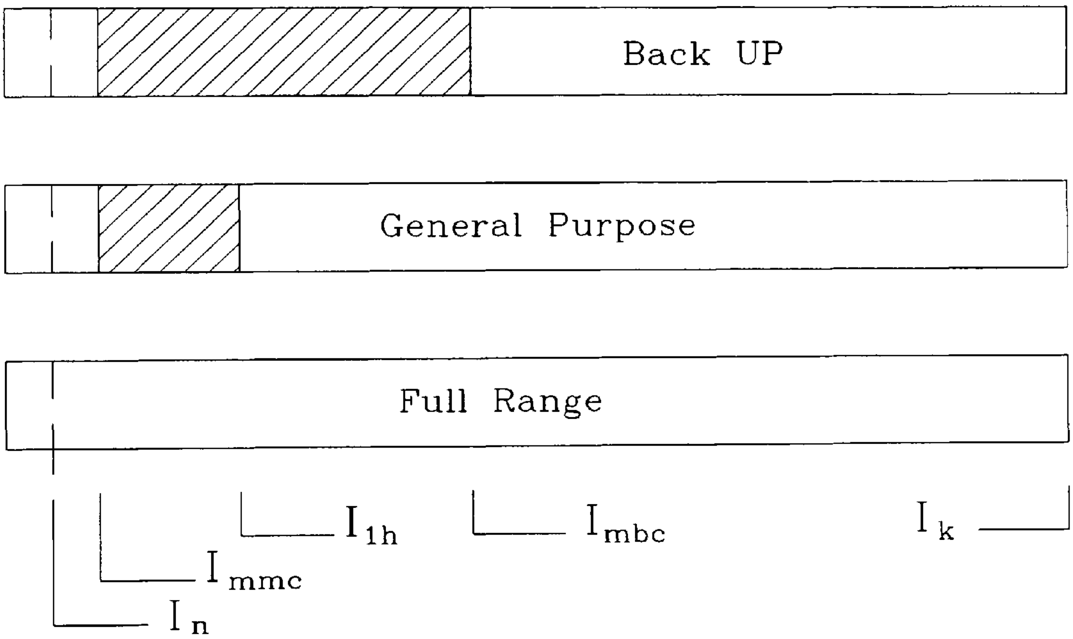
- The fuse-link to be tested is placed in a low voltage test circuit and a current equivalent to the one hour current or less is allowed to flow through the fuse.
- A high-voltage test circuit (at the fuse-links rated voltage) is pre-adjusted to provide a current equal to or less than the original low-voltage pre-heating current (this may not be less than 70 % of this pre-heating current).
- This low-voltage current should be maintained until all elements have melted. It is permitted to increase the value of current up to 1.15 times the original value after a period of one hour to ensure melting of the fuse elements.
- When the fuse elements have melted (but not the striker if fitted) the fuse is switched over to the high-voltage source in a time of 0.2 seconds or less.
- The value of this high-voltage current may be claimed as the minimum breaking current by the fuse manufacturer provided that the fuse re-strikes immediately on application of the high-voltage source and successfully operates and clears in the normal manner.

One of the drawbacks of testing to this latest standard is that if the claimed minimum breaking current is required to be lower than 70 % of the current corresponding to the one hour pre-arcing time (this is often the case when testing the fuses down to their

their rated current), then lower values of pre-heating current and hence longer pre-arcing times are necessary.

In order to avoid unnecessarily long testing times, the fuse-link under test may be installed in an enclosure with restricted cooling to reduce the pre-arcing time so long as this reduced time shall be not less than one hour.

Figure 5 shows the Zones of Uncertain Operation of Back-Up and General-Purpose fuses i.e. the zones in which there is no certainty that these fuses will be able to interrupt the current after melting of the fuse element has begun.[12]



I_n = rated current of fuse

I_{mmc} = minimum melting current of fuse

I_{1h} = current which causes melting of fuse element in 1 hour

I_{mbc} = minimum breaking current of fuse

I_k = maximum breaking current of fuse

Figure 5 The zones of uncertain operation of Back-Up and General-Purpose fuses

2.3 Methods of Achieving Full Range Performance

Full-Range fuses have found widespread use in the USA, Western Europe, Japan and Australia. They have been available in the U.K. for approximately 10 years and are now beginning to be used more extensively. There are two common design philosophies used in the achievement of Full Range performance fuse links.

2.3.1 Combination of Back-Up and Expulsion Fuse Elements

The first common method involves the combination of a miniature expulsion fuse element in series with standard current limiting 'back up' type fuse elements all within a standard fuse body. This type of fuse is designed so that the expulsion elements clear low fault currents whilst the current limiting elements clear the high fault conditions in the same way as conventional h.b.c. fuses. [13]

The intersection of the expulsion and current limiting portions of the fuses are usually arranged so as to coincide approximately mid-way between the minimum breaking current of the current limiting elements and the maximum breaking current of the expulsion elements.

This type of technology utilises the advantages of the expulsion fuse technology in that it can be designed to have excellent low-overload breaking performance and also the current limiting fuse technology enabling it to have a virtually unlimited maximum breaking capacity and extremely effective current and high energy limitation during operation. This results in a time current characteristic which approximates closely to the ideal characteristic of a HV fuse. Figure 6 shows how the time current characteristics of the expulsion and current-limiting fuse elements can be arranged to complement each other and produce a good time-current characteristic.

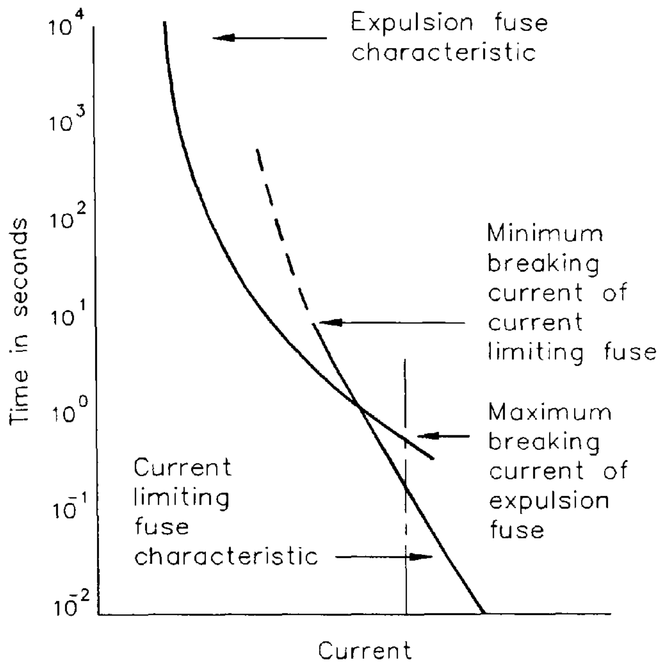


Figure 6 Combination of expulsion and current-limiting fuse elements and their operating characteristics

The disadvantage of this technology is that the problems requiring solutions in the design of an integral full-range fuse are of considerable complexity. The electrical characteristics of the current-limiting and expulsion element systems have to be matched with some precision to ensure that the minimum breaking current of the main elements, is well below the 'take-over' point, that is the intersection on the time/current curve of the expulsion and main element curves. At the same time, the maximum breaking current of the expulsion elements has to be well above the take-over point.

The breaking tests that are carried out to prove the performance of high voltage fuse-links are defined in three test duties:

Test Duty 1 is the high current rated maximum breaking capacity test.

Test Duty 2 is verification of operation under maximum arc-energy conditions in the current limiting region.

When a fuse-link is clearing a fault, there is an amount of stored energy in the inductive elements of the circuit when arcing commences. Test duty 2 simulates the conditions which cause the arc-energy to be at a maximum. The approximate relationship between the stored energy and prospective current is shown in figure 7. It can be seen that the stored energy decreases with an increase in prospective current over the range of currents where current limitation occurs. At lower currents however, it is proportional to the prospective current therefore, there is a current at which the stored energy is the greatest - this is often referred to as the critical current of the fuse-link. As a general rule the value of the current I_2 lies between three or four times the current which corresponds to a pre-arcing time of one half-cycle on the time current characteristic.

Test Duty 3 is the low current test, for back-up fuses this is the minimum melting current; for general purpose fuses it is the current which causes melting in one hour; for full-range fuses it is generally taken to be rated current (where testing to the value is practical).

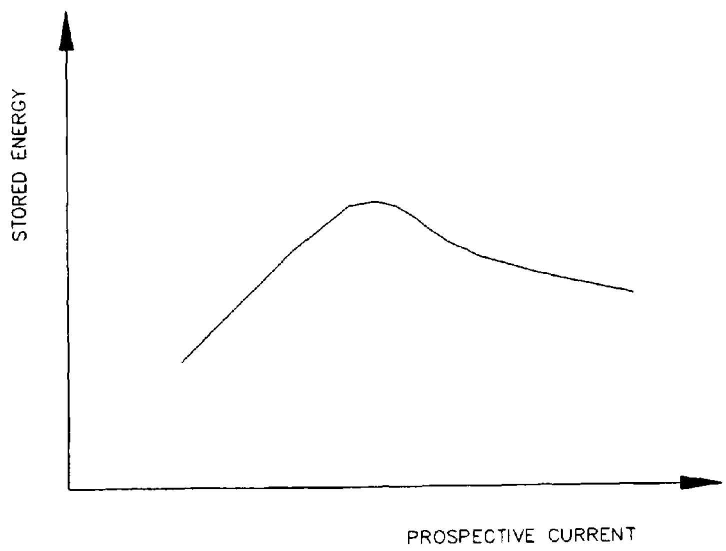


Figure 7 Variation of stored energy with prospective current for current limiting fuse-links

When full range fuses are manufactured using this two part technology, extensive testing also has to be carried out in the region of the 'take-over' point to ensure that there is safe operation over the whole range of fault currents.

2.3.2 Large Numbers of Thin Fuse Elements in Parallel

The minimum current which can be cleared by fuse-links with conventional strip type elements can be reduced in two ways. Firstly by employing elements with long restricted sections of small cross-sectional area and secondly by using a large number of parallel-connected elements of small cross-sectional area rather than a smaller number of thicker elements [8].

Introducing longer restrictions in the fuse element means the design has longer sections that have a high current density (the restriction would also be running at a elevated temperature due to the 'heat sink' of the main strip being further away from the centre of the notch). During arcing it would therefore be easier for the fuse to build up its resistance and break the fault current.

The mode of operation of a large number of parallel elements can be explained as follows : after all fuse elements have melted there will be one element or arc which conducts the current as the arcs cannot exist in parallel to each other. An arrangement of thin elements therefore enables a relatively high current density to be present in each individual strip during the arcing period. Due to this high current density the strip will melt at the element constrictions causing multiple arcing. This ensures that all currents are broken in a current limiting way.

It therefore follows, that if you have an arrangement of a large number of thin fuse elements of conventional design in parallel, the minimum breaking current can be reduced to the rated current of the fuse-link and below, provided that the cross-sectional area of the elements is reduced sufficiently.

The main advantage of this technology is that the designs are of a simpler nature utilising only one type of technology to achieve full range performance. Again the fuse-link will have a virtually unlimited maximum breaking capacity.

The necessity of having a great number of thin elements in parallel however, can in itself prove to be a disadvantage. With traditional manufacturing methods this concept was fraught with problems due to the difficulty of manufacture and element fragility.

However, during the early part of the 1980's, a Dutch company - Holec Systemen en Componenten - introduced a totally unique and novel method of manufacture which enabled these problems to be overcome and they developed a series of full range HV current-limiting fuse links, known as 'Fullran'. [14]

2.4 The 'Fullran' Full Range Fuse-Links

Fullran current-limiting fuse-links were developed for full protection of distribution transformers against the effects of both overload and short-circuit currents. They are capable of interrupting all currents which cause melting of the fuse-element.

To overcome the vulnerability of the notched strips of fuse element Holec developed a method of manufacture whereby the silver fuse strips are attached to a quartz glass tube and are therefore supported over their entire length. This makes it possible to arrange a large number of thin conductors parallel to each other.

The parallel elements are provided in the middle with a low melting point metal (tin) known as the tinspot or 'M-effect' (named after the Metcalf effect). [15] The elements are connected at the two ends of the quartz tube by 'collars'. Connections can then be made between the fuse end caps and the quartz tubes. Further construction and manufacturing details are given in chapter 3.

2.4.1 The 'M-Effect'

The M-effect can be simply described as follows. [16]

A low melting point alloy (e.g. tin) is deposited onto the surface of a silver fuse element. This spot of tin acts as a low melting-point metal. As electric current passes through the fuse elements heat is produced. As the current increases so the temperature increases until eventually the melting point of the tin is reached. Once in the molten state the tin readily diffuses through the silver element forming tin-silver compounds. The tin-silver compounds have a much higher resistivity value than that of pure silver. Therefore the current seeks a path through any reduced silver path that remains. This results in a much higher current density and hence a further increase in temperature at this point. The rate of diffusion will then increase causing a further increase in temperature etc. until the tin completely diffuses through the silver element and fuse operation occurs.

This enables the fuse element to melt at a significantly lower temperature - approximately 230°C (the melting point of tin) as opposed to 960°C (the melting point of silver).

2.5 Advantages of Fullran Fuses

It can be seen that Fullran fuses are designed and constructed in a completely different way to traditional fuses. As previously discussed this change in design enables full-range performance fuses to be produced without the need of placing expulsion elements in series with back-up elements. There are also other distinct advantages associated with this new method of construction.

2.5.1 Mechanical Ageing

As a result of load variations above the rated current, changes in temperature in the fuse strips can cause material fatigue as a result of expansion and contraction in the surrounding sand. Consequently one or more fuse strips can break, which means a General Purpose or a Back-Up fuse has to operate in an area where it is not certain that the current can be broken. As explained in section 2.3.2., the minimum current which can be cleared by fuse-links, using conventional strip elements, is a function of the number of parallel-connected elements and their cross-sectional area. Therefore if one or more fuse strips break, the minimum current which it can clear increases, thus extending the zone of uncertain operation as shown in figure 5.

Fuses are generators of heat, which must be dissipated to its connections and mountings by conduction and convection and by radiation from its surfaces. The IEC 282-1 standard [5] lays out conditions for special tests to determine the power dissipation of fuse-links when it has reached a steady value for test currents of 50 % and 100 % of the rated current. The power dissipation is expressed in Watts and is generally referred to as the 'Watts loss'. Watt losses of HV fuse-links at rated currents can reach rather high values, particularly for fuse-links that are designed without a low melting-point alloy. In an enclosed installation with restricted ventilation this can mean that the rated current of the fuse-link has to be adjusted i.e. the fuse has to be de-rated.

The aim of a good design is to keep the Watts loss to a minimum [7] which will therefore keep the temperature rise of the fuse-links low. Like the majority of HV fuses manufactured with low melting-point alloy Fullran fuse-links have relatively low Watt losses therefore the temperature rise is limited, and because the fuse strips are firmly attached to the supporting tube over their entire length, mechanical ageing is virtually eliminated. Watts loss figures and characteristics are shown in Appendix D.

2.5.2 Thermal Ageing

Fuses loaded for long periods above the rated current, but not quite reaching the minimum melting current, are liable to age thermally at the M-spots. During periods of overload, temperatures can be reached such that the diffusion process starts, without melting occurring. This causes the I-t characteristics of the fuses in the low overload ranges to alter so that the fuse link operates faster. With General Purpose and Back-Up fuses, there is again the danger that the fuse link will melt in an area where it is not certain that the current can be broken. If the fuse is used for transformer protection ageing hardly occurs since the rated current of the transformer is usually considerably lower than the rated current of the fuse. Since Fullran fuse links can break all currents at which melting occurs, a change in characteristics due to thermal ageing will not cause damage to the switchgear as the Fullran fuse has no zone of uncertainty and the fuse will operate successfully.

2.5.3 Handling

Due to the fuse elements being attached to the quartz tube, the problem of element breakage sometimes associated with traditional 'wound element' fuses is eliminated. The fuses are therefore robust and are shock and vibration resistant requiring no special handling.

2.6 Disadvantages of the Fullran Fuse

Although the Fullran fuse was a major technological development in fuse design, it had a number of undesirable characteristics which precluded it from becoming a major commercial success.

2.6.1 Time / Current Operating Characteristics

Whilst there are no standard time-current characteristics which fuse-links have to match, there are a number of defining factors and gates through which the time-current curve of the fuse-link should pass. These gates are laid out in various standards. Two standards that particularly apply to transformer protection and hence the Fullran fuse are ESI 12-8 [18] and IEC-787 [19].

The market requires reliable protection in the melting time region of approximately 1 second to a few hours. The IEC 787 publication says about this point:

> "Time/current characteristics of HV fuse-links for transformer circuit applications should have a relatively low operating current in the 10 second region so as to ensure rapid clearance of transformer winding faults, secondary side earth faults, and to give good co-ordination with overcurrent protective devices on the source side".

The pre-arcing time/current characteristics of fuse-links for transformer circuit applications, should preferably therefore be within the limit:

$$\frac{I_f \bullet 10}{I_n} \leq 6$$

Where,

I_n = current rating of the fuse-link and

$I_f.10$ = pre-arcing current corresponding to 10 seconds.

The ESI 12-8 Standard sets out the general requirements for the operating characteristics of High Voltage fuses as follows:

A high voltage fuse-link in a fuse-switch combination protecting a given rating of transformer should:

i. Be capable of carrying continuously the appropriate value of current specified when fitted in the combination. - The HV fuse-link minimum rated current in the combination.
ii. Withstand certain specified periodic transformer overloads.
iii. Withstand transformer magnetising in-rush current. For this purpose a fuse-link is deemed satisfactory if it withstands, without deterioration, ten times transformer primary full load current for a period of 0.1 s.
iv. Operate within 1 s for a 3-phase fault in the terminal zone of the transformer secondary winding.
v. Discriminate reliably with low voltage fuse-links up to the maximum current available for a fault on the low voltage side of the transformer.
vi. Discriminate predictably with up-stream protection.
vii. Be capable of causing the fuse-switch combination to interrupt satisfactorily all values of fault current up to the rated breaking current of the combination.
viii. Not be used on systems where the potential short circuit current exceeds the rated breaking current of the fuse-switch combination.

This selection criteria can be shown on a time-current graph giving the various gates through which the fuse-links characteristics should pass. Figure 8 shows these gates and highlights the disadvantage of the Fullran fuse-links in that they fail to pass through some of these specified gates.

It can be seen from figure 8 that the prominent 'belly' in the Fullran operating curves mean that the fuse-link will not operate quickly enough in the 1 second region - i.e.

for a 3-phase fault in the terminal zone of the transformer secondary winding. It also fails to meet the operating limit set out in IEC-737 i.e.

$$\frac{I_f \bullet 10}{I_n} \leq 6$$

The very fact of having a large number of elements in parallel with each other means that there is a large surface area of silver from which the heat generated in the elements can be dissipated. Also as the elements are attached onto a quartz tube there will be a greater amount of heat lost to the surrounding media.

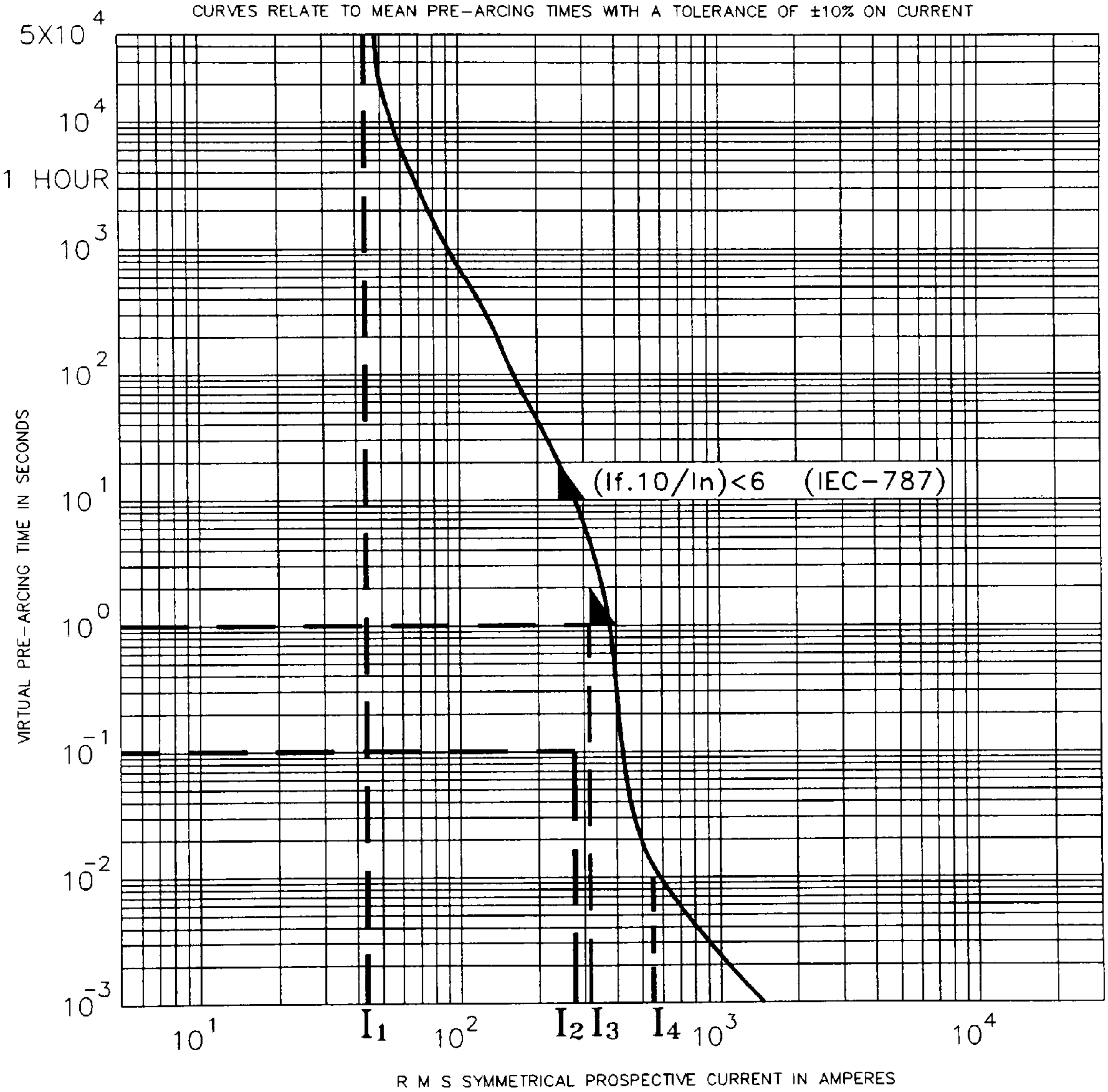
This combination means that the standard Fullran element design takes longer to operate (than conventional designs with similar current densities) in the region between low overload faults, (approximately 1 hour or greater operating times), and short circuit faults, (virtually instantaneous operation, that is times < 1 ms, with minimal heat losses).

When Holec designed the Fullran fuse-links, they were aware of the unfavourable operating characteristic of the design but continued with them as the characteristics do not prevent the designs from being sold into the Dutch utility market. However, this failure to meet the specified gates above limits the potential sales to countries which strictly adhere to these transformer protection standards such as the UK.

2.6.2 High Material Costs

Compared with Back-Up and other types of full-range fuses the material costs of the Fullran designs are significantly higher. Whilst some of the cost could quite easily be engineered out of the product, the cost of the clear quartz tube keeps the material costs high. The physical properties required of the substrate material means alternative materials are difficult to source. Efforts are underway to try and reduce the cost of the substrate material.

Transformer Protection Operating Gates
For a 500 KVA Transformer &
The Characteristic of a 40 Amp Fullran Fuse



I_1 — Minimum acceptable rated current of fuse-link.

I_2 — Magnetising inrush current that fuse-link must withstand.

I_3 — H.V. current for 3-phase fault in the l.v. terminal zone that must be cleared within 1 second.

I_4 — Maximum h.v. current at which discrimination with l.v. fuse-link is required.

Figure 8 Transformer protection operating gates for a 500 kVA transformer and the 40 A Fullran curve

2.7 Summary

This chapter introduced the concept of full range fuses and the different design methods for achieving full range performance.

The chapter also introduced the 'Fullran' range of high voltage full range fuse-links showing the advantages gained through its unique design and also its disadvantages particularly its time-current operating characteristics.

Chapter 3 will give further details of the methods of construction and manufacture of the Fullran fuse-links and highlight how the Teaching Company Programme objectives relating to manufacture were addressed.

3. Manufacture of the Fullran Range of Fuses

The preceding chapter introduced the Fullran range of high voltage full range fuse-links which were originally developed by Holec Systemem en Componenten, and how in order to overcome the vulnerability of the notched strips of fuse element Holec developed a method of manufacture whereby the silver fuse strips are attached to a quartz glass tube and are therefore supported over their entire length.

3.1 The Fullran Manufacturing Process

In order to produce the silver elements onto the quartz tube former Holec developed a unique process whereby the fuse element pattern is silk screen printed on the tubes with silver ink/paste.

After the paste has naturally dried, the tubes are placed on racks and put in an oven for a set amount of time at a very high temperature (between 550°C and 850°C). This has the effect of curing the paste and driving away any impurities leaving a silver layer adhered to the surface of the quartz tubes.

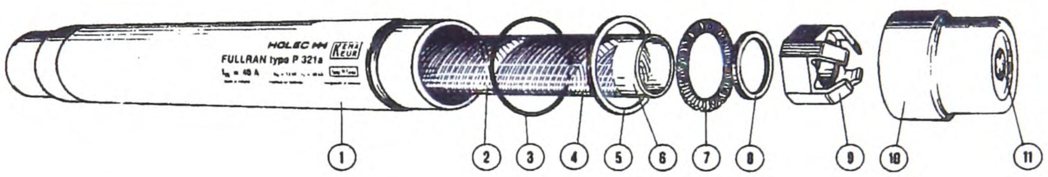
The tubes can then be placed onto a silver plating machine which enables more silver to be deposited onto the fuse elements to thicken them up and achieve the different current ratings (see section 3.2).

Depending upon their rated current, Fullran fuse-links are supplied in two different series.

For rated currents of 6.3 - 40 A (12 kV), the parallel fuse-strips are attached to one supporting tube. The various ratings only differ in the thickness of the fuse-strips and hence in their resistance value. Otherwise the fuse-link designs are identical.

For rated currents of 50 - 80 A (12 kV), the fuse-element consists of a greater number of parallel strips attached to two concentric quartz tubes. Again the fuse-link designs are identical apart from the thickness of the fuse-strips.

Figure 9 shows an exploded view of a Fullran fuse-link. The quartz glass tube (2) has the silver fuse-strips (4) attached which are connected by common 'collars' (6). The contact between the collars and the silver plated end cap (10) is made by a toroidal contact spring (7) ensuring a good electrical contact between the end cap and the fuse-element. This contact spring also secures the tube centrally inside the porcelain barrel (1). A plastic flexible spacer (9) and a rubber buffer ring (8) ensure axial centring and protection of the supporting tube against shock and vibration. A rubber washer (5) on the extreme ends of the porcelain barrel and a silicon rubber band (3) in a positioning seal provide an air tight seal. After the fuse-link has been filled with very fine silica sand, the filling hole is sealed with a gas-tight blind rivet (11).



1 - porcelain barrel
2 - supporting tube
3 - rubber band
4 - fuse-strips
5 - rubber washer
6 - sleeves
7 - contact spring
8 - buffer-ring
9 - spacer
10 - end cap
11 - rivet

Figure 9 Exploded view of a Fullran fuse-link

Figure 10 Photograph of a Fullran element assembly and a finished fuse-link

The manufacturing flow chart is shown in figure 11.

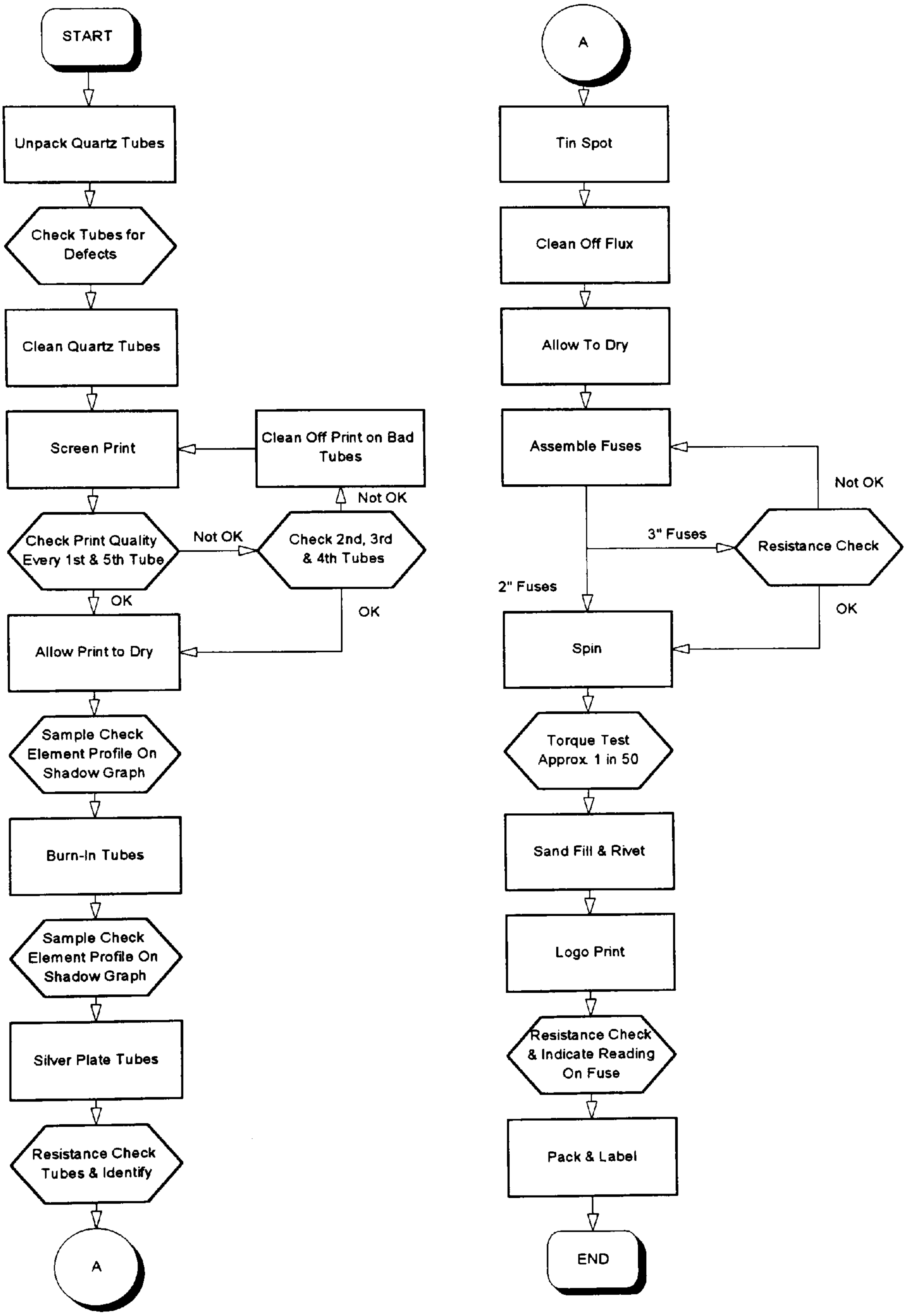


Figure 11 The Fullran manufacturing process

3.2 The Electroplating Process and the Commissioning of a New Plating Plant

In chapter 1 it was shown that one of the specific overall objectives of the Teaching Company Programme was 'to introduce new more sophisticated plant and equipment for improved production efficiency and to release existing plant for product development'. Just prior to the commencement of the programme, B & S Fuses had invested heavily in a new purpose built electroplating plant for the production of the Fullran type fuse.

The plating plant was mechanically designed and built by Holec Systemen in collaboration with another Dutch firm, ProfTech Systemen B.V., who provided the Programmable Logic Controller (PLC) controlled electrical system. A schematic of the plant is shown in figure 12 below.

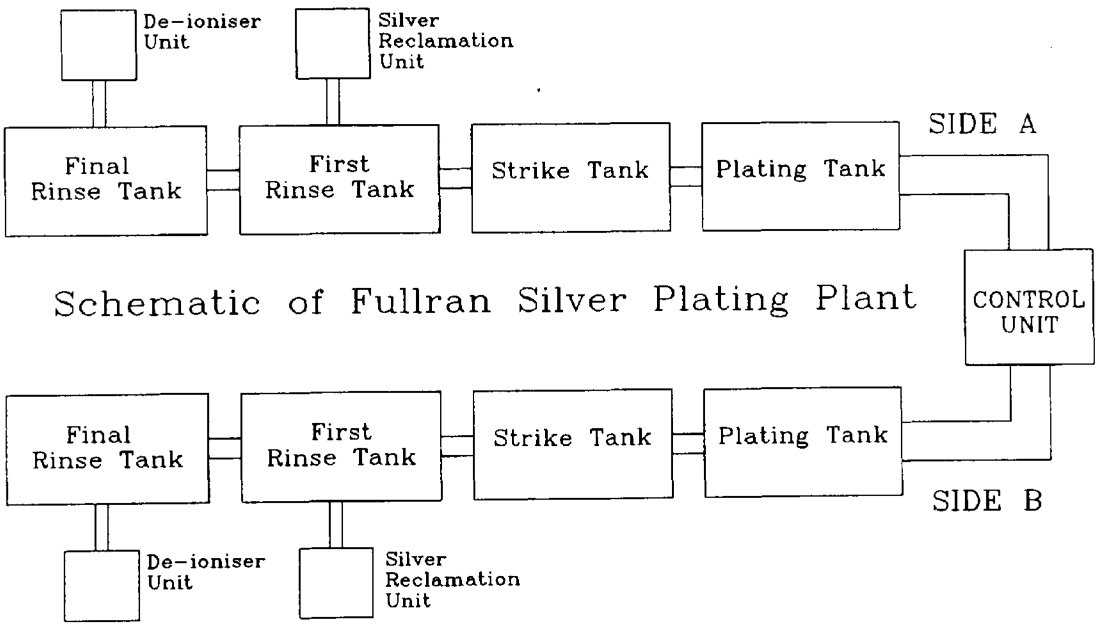


Figure 12 Schematic of Fullran silver plating plant

Almost immediately upon commencement of the Teaching Company Programme, the commissioning of the new plant began. For a period of one week Holec and ProfTech engineers visited the B & S factory to commence commissioning. From the mechanical standpoint, the commissioning of the plant went relatively smoothly.

Unfortunately, the electrical / control side proved to be extremely troublesome requiring a lot of effort from the author, B & S Fuses staff and ProfTech engineers.

In order to make alterations to the programme, a basic understanding of the required process is needed. This process is simply described in the following section.

3.2.1 Overview of the Operation of the Plating Plant

Every electroplating bath contains electrically equivalent amounts of positively charged particles (cations) and negatively charged particles (anions) dissolved in a solvent, usually water.

Electroplating is performed by passing a direct current through the solution between one or more anodes, connected to the positive terminal of the DC source, and one or more cathodes (the work to be plated), connected to the negative terminal. In the external circuit, negatively charged electrons flow from anode to cathode via the power source. Within the solution, all the cations migrate under the influence of the electric field towards the cathodes and all the anions towards the anodes. Different types of ion move at different rates, depending mainly upon their size and the magnitude of their charge. The sum of their movements in both directions produces a total flow of charge, i.e. current, equal to the external current. [17]

In the case of the Fullran plating plant, the plating bath is a silver cyanide type; the main constituents being: potassium cyanide, silver cyanide, potassium, carbonate and a certain amount of brightener or hardener. The anodes are slabs of solid silver that sit in the plating solution (polarised by connection to 'anode bars' by way of two titanium racks). These silver anodes are soluble; that is, when the current is flowing the metal ions in their surface lose electrons and pass into the solution as ions. The cathodes are the quartz tubes with screen printed silver layer deposits. A current of up to 2.5 amperes is passed through the external circuit causing more silver to be deposited onto the element tracks on the tubes.

The operation of the plant purchased for the production of the 'Fullran' fuse is described in the following steps:

- A target resistance for the tubes, the initial plating current, the initial plating time and the second plating time (a factor dependent upon first time) are input into the control unit.
- The unplated tubes are loaded onto the racks in the loading position.
- The transporter moves the rack over the strike tank and dips the tubes in twice.
- The transporter moves the tubes over the plating tank and their resistance is measured.
- The tubes are submerged in the plating solution and the set plating current is passed through the tubes for the set period of time.
- The tubes come up out of the solution and their resistances are measured.
- The PLC calculates the required second current for each position in order for the tubes to reach the set target resistance.
- The tubes are submerged again for a fraction of the first plating time (depending on the factor setting) and are plated at the individually calculated second currents.
- The tubes come up and their final resistance values are measured.
- The transporter moves the tubes over the strike and two rinse tanks in turn, dipping the tubes twice into each tank.
- The finished tubes are unloaded.

Some examples of programming errors that were encountered during the commissioning period were: in the control of movement of the transporters e.g. dipping in the rinse tanks prior to plating; the way in which resistance measurement took place; the calculation of the second plating current; the way in which the programme dealt with measuring and calculation errors and the calibration sequence of the machine.

The combination of the necessary programme changes, modifications to some electrical control circuitry and the elimination of general teething problems, meant that the commissioning of the plating plant took up a great deal more time than was allocated in the original Teaching Company Programme plan. However, the commissioning had to be given priority as the whole development programme greatly depended upon the extra capacity being available with the new plant.

One bonus in the time spent on the commissioning was the thorough knowledge of the plant and equipment gained through the work carried out. This enabled detailed procedures for the operation and maintenance of the new plating plant to be drawn up consisting of:

- Plating plant operating guidelines, written to help instruct the operator in the use of the new plating plant, and highlight potential problems and their possible causes. (See Appendix A).
- A planned maintenance / general housekeeping guide, listing the daily, weekly, fortnightly, monthly and six monthly checks and tasks required to help keep the plant running smoothly and effectively. (See Appendix A).

3.2.2 Quality and Health & Safety Issues

As shown in chapter 1, at the time of the commencement of the Teaching Company programme on of the key objectives of B & S Fuses was to obtain full quality approval to BS 5750. The company had recognised the need for a total quality system to be implemented throughout for them to be able to satisfy customer requirements properly. To achieve this, a structured control system from receipt of an enquiry through manufacture, supply and liaison to after sales service had been set up. The system adopted was structured in such a way as to comply with the requirements of BS 5750 :part 2 (ISO 9002).

The initial goal of the company was to achieve approval for the manufacture of the traditional Back-Up and General-Purpose fuses. This approval was to be followed by extending the scope to incorporate the Fullran full-range fuse manufacture and finally the press shop, fuse mounts and fuse cut-out sections of the business. B & S was successful in obtaining the approval for Back-Up and General-Purpose fuses in November 1993.

Through Holec, the Fullran product had already been awarded the prestigious Kema-Keur certificate of quality assurance essential to the Dutch Market. B & S had maintained the high standards of quality necessary to retain the certificate after the transfer of manufacturing in 1990. The work of updating and modifying the inspection, test and manufacturing procedures for the Fullran fuse, so that they followed the format of the Quality Assurance manual adopted by the company, was undertaken by the author as part of the Teaching Company programme in conjunction with the quality department of B & S Fuses.

Detailed process procedures were laid down for all processes from unpacking of the quartz tubes through to packing and despatch of the final product. The procedures covered the following points for all sections:

Policy	The reasoning behind the document / procedure.
Scope	What the procedure applies to.
Procedure	The actual method of carrying out the process
Notes	Indicating any other relevant details such as how machines should be set up, what visual inspection to perform whilst carrying accordance with the in-process inspection schedule) etc.
Important	Providing Health and Safety information e.g. what ventilation units must be switched on, the location of emergency stops, and any protective equipment which should be worn.

Alongside the production procedures document was the 'In-process Inspection Procedures' manual. This document laid down quality checks to be carried out by the operators (with the aid of the QC department if required). The procedures stipulated the type of testing to be carried out, the frequency of the checks and showed the tables / charts on which the information was to be compiled. The process checks included element parameter measurement after printing, burning-in and plating; sand compaction, striker operation, torque tests on the spun end caps and radiographic inspection.

An example of one section of production procedures and one of the charts used during the in-process inspection is shown in Appendix A.

3.3 Comparison of Manufacturing of Fullran and Traditional Fuses

It can be seen that Fullran fuses are manufactured in a completely different way to traditional fuses (see figures 1 & 10). The method of manufacture of the Fullran fuses has two distinct advantages over traditional methods.

3.3.1 Consistent High Quality

The method of manufacture ensures consistency in the quality of the fuses produced with regard to element spacing and the profile of the fuse elements. Once again due to the elements being attached to the quartz tube there is no chance of the elements breaking or moving during the assembly processes. Therefore the number of fuses requiring rework after assembly and sand filling is negligible. This is compared with traditional designs where element movement or breakage's can occur during the process of welding the element assembly to the end caps or during the sand filling process. (Typically 2 % of fuses would be scrap due to element damage after final assembly).

3.3.2 Labour Costs

The nature of the Fullran manufacturing process lends itself to high volumes and is significantly less labour intensive than traditional manufacturing processes, generally showing a 50 - 60 % reduction in labour costs of comparative fuse-links.

3.4 Summary

This chapter explained the manufacturing process for the Fullran range of fuses and the manufacturing and quality issues dealt with during the Teaching Company programme. Whilst there are advantages in the manufacturing process as highlighted in section 3.3, and some technical advantages described in chapter 2 section 2.5, there were some problems which needed to be addressed, (see section 2.6).

In order to further develop the Fullran design and turn it into a commercial success, the material cost and more significantly the operating characteristic problems need to be addressed. However before expending money and scarce resources on this development, the following fundamental question must first be asked:

If Back-Up style fuses have been used to good effect for so many years;

- Why bother with full-range fuses at all ?

and more specifically,

- Why develop the Fullran fuse to meet the international standards ?

Chapter 4 will address these questions.

4. Traditional Fuse Application, Trends and New Concepts in System Protection

4.1 Traditional Fuse-Link Application

For over 40 years h.b.c. fuses have played an integral part in the protection of distribution systems / networks. Their low cost, high reliability and compact nature have made them an ideal choice for widespread protection use.

In the U.K., the practice has been to fit the h.b.c. fuses on the primary side of the distribution transformers as part of fuse/switch combinations or Ring Main Units (RMU's) see figure 13 below.

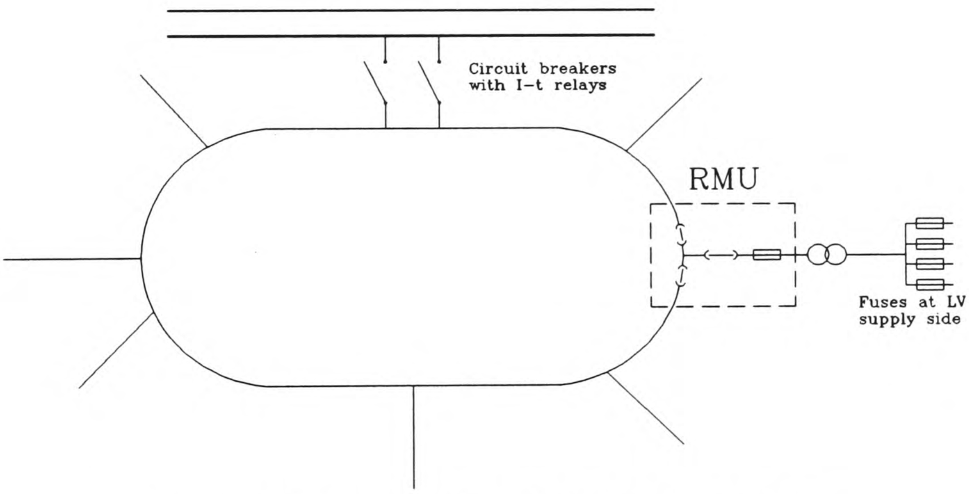


Figure 13 Schematic of an 11kV Ring Main System

The 11 kV ring-main passes through the ring circuit of the RMU and the fuse tee-off circuit feeds the step-down distribution transformer. This set up enables the ring main to be opened either side of the tee-off point which assists with the location and isolation of faults ensuring continuity of supply to more areas. [20]

Most of the RMU's used in the U.K. are the oil-filled variety where the switches, fuses and connections are all immersed in an oil filled chamber. This has provided a compact protection unit with a high reliability and low maintenance cost. RMU's have been amongst the safest of all distribution equipment with only a very small number of serious incidents reported during the products lifetime. [21]

4.2 Market Analysis

4.2.1 Forces Driving Industry Competition

Taking the High Voltage fuse-link product as a whole:

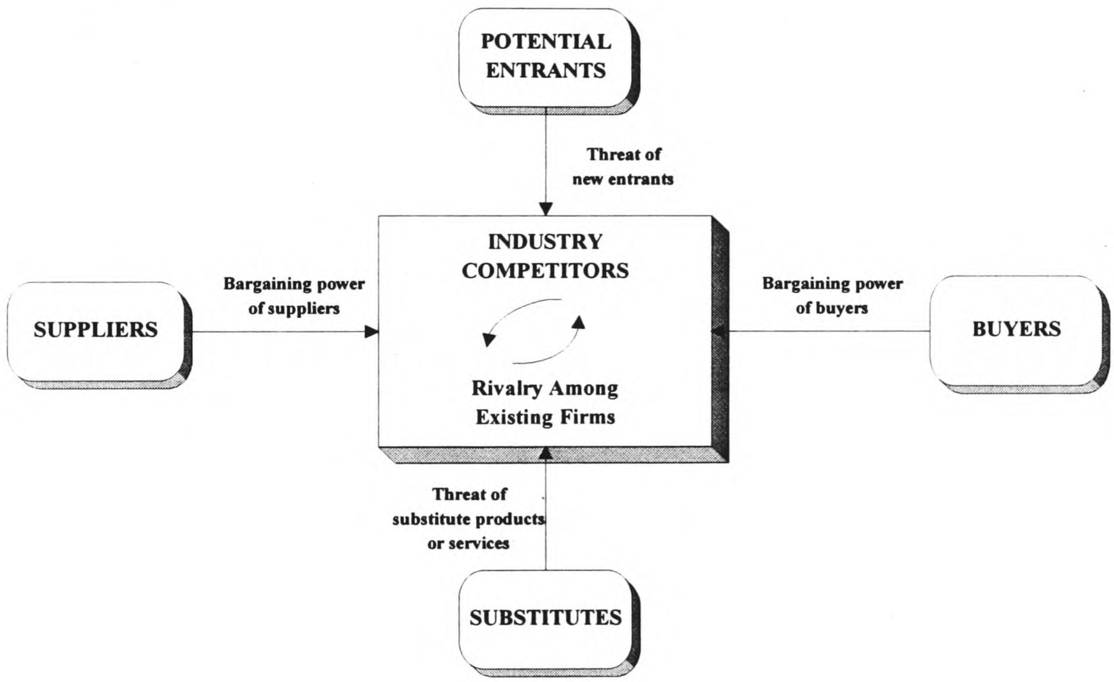


Figure 14 Forces driving industry competition

4.2.1.1 Threat of Entry

The threat of new entrants into the market is relatively small in the established Home, Western European and British influenced markets, due to the high barriers of entry. The threat does increase in World markets where price has a bigger influencing factor.

The main barriers to entry for anyone wishing to enter the industry in the High Voltage fuse-link market are:

Product Differentiation. The established fuse-link companies have a brand identification and customer loyalty stemming from customer service, product differences and a 'tradition' in the market. This 'product differentiation' creates a barrier to entry by forcing entrants to spend heavily to overcome existing customer loyalties. Such investments in building a brand name are particularly risky since they have no salvage value if entry fails.

Economies of Scale. Economies of scale refer to reductions of unit costs of a product as the absolute volume period increases. Scale economies can be present in nearly every function of business, including manufacturing, purchasing, research and development, marketing, service network, sales force utilisation and distribution. Therefore trying to compete against large existing manufacturers can prove to be very difficult.

Capital Requirements. The need to invest large financial resources in order to compete creates a large barrier to entry. The product development and certification costs necessary to have a viable product in this market would result in an enormous outlay of capital. Another large cost, and hence significant barrier, would be the purchase of the specialist manufacturing equipment and the development of suitable manufacturing techniques.

4.2.1.2 Competitive Forces - Existing Competitors

Rivalry amongst existing competitors is fairly intense due mainly to equally balanced competitors and slow industry growth.

4.2.1.3 Competitive Forces - The Customer

Buyers compete with the industry by forcing down prices, bargaining for higher quality or more services, and playing competitors against each other. The largest traditional buyer group of HV fuse-links has been the UK and World Electricity Utilities, either for new fusegear installations or for their replacement needs. Therefore, as most fuse-links were purchased for fuse/switch units it has meant that the cost of the fuse-links represented only a small fraction of the buyer's cost so no undue pressure has been applied. However increasing competition between existing fuse manufacturers and the recent economic recessions have increased this pressure.

4.2.1.4 Competitive Forces - The Suppliers

Suppliers can exert bargaining power over participants in an industry by threatening to raise or reduce the quality of purchased goods and services. Powerful suppliers can thereby squeeze profitability out of an industry unable to recover cost increases in its own prices. The number of available alternative suppliers for the components that make up HV fuses has ensured that no supplier can achieve an excessive amount of bargaining power.

4.2.1.5 Competitive Forces - Pressure from Substitute Products

All firms in an industry are competing, in a broad sense, with industries producing substitute products. Substitutes limit the potential returns of an industry by placing a ceiling on the prices firms in the industry can possibly charge.

Substitute products that deserve the most attention are those that (1) are subject to trends improving their price-performance trade off, with the industry's product, or (2) are produced by industries earning high profits. In the latter case, substitutes often come rapidly into play if some development increases competition in their industries and causes price reduction or performance improvement.

The pressure from substitute products may pose the biggest threat to the future HV fuse industry. There has been a developing trend towards the use of circuit breakers in protection systems rather than the traditional RMU's. This trend is due to a number of factors but primarily the perception that oil filled RMUs are dated technology coupled with the environmental implications of having oil filled equipment.

4.2.2 Product Lifecycle

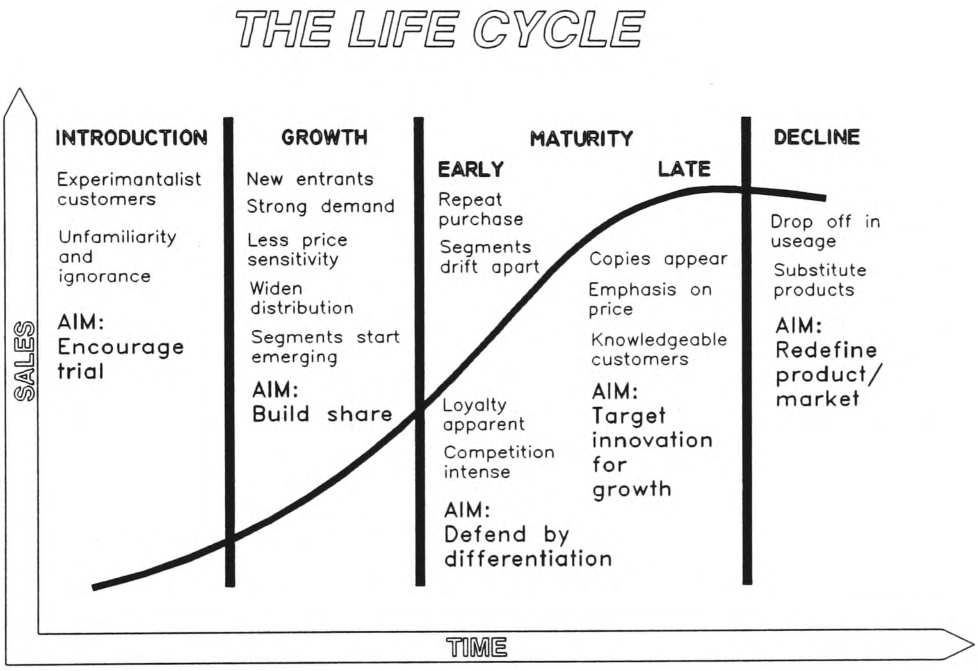


Figure 15 The lifecycle of a product

Applying figure 15 to HV fuse-links, it can be argued that they are situated somewhere between Late Maturity and Decline. As it can be seen from the diagram the aim for products in these areas of life cycle is to 'target innovation for growth and redefine product / market'. This is where the Full Range classification of fuse-links comes into play and with it the idea of transformer protection using Fuse End Boxes (see section 4.3.2). [22]

4.3 New Protection Trends

Since the privatisation of the Electricity Boards and the subsequent formation of the Regional Electricity Companies (REC's) in 1990, questions have been asked about long standing policy's on protection. Whilst there has been an initial upturn in fuse-link requirements due to an extensive period of refurbishment, there has been a lot of debate concerning the replacement of existing ageing RMU's and the protection policy for new installations.

Much of the debate stems from the perception that due to their age, and the environmental considerations of using oil, Ring Main Units consist of dated technology that will therefore have a disadvantage over new protection gear. Subsequently there has been a lot of interest shown in alternative protection equipment.

4.3.1 SF6 Circuit Breakers

There is a trend towards the utilisation of SF6 circuit breakers in electricity distribution networks. There are a number of advantages in using SF6 switchgear which must be balanced against some disadvantages.

SF6 gear is marketed as 'sealed for life' and would therefore be maintenance free. Obviously if this was proved to be true, it would be a distinct advantage over other types of switchgear such as oil filled switchgear. Another advantage of SF6 gear is that unlike the oil filled RMU's (or oil filled circuit breakers), a malfunctioning SF6 unit would be very unlikely to catch fire.

One final advantage relates to circuit breakers generally over RMU's and that is that circuit breakers enable remote switching and isolation of faults which can save a great deal of time for switching operations and loss of supply to customers.

There are however some disadvantages with using SF6 circuit breakers. The first major disadvantage is cost, at present, the SF6 equipment is approximately 50 % dearer than the RMU's they replace. Another factor that needs consideration is that SF6 circuit breakers do not yet have the proven long term safety record of the RMU's.

Another disadvantage is common to all non current-limiting devices, such as circuit breakers, as opposed to switch/fuses and fused RMU's and that is that they are unable to provide 'cut-off' or current limitation under severe circuit fault conditions.

AC circuit breakers work by preventing re-ignition of the arc when the fault current passes through zero. Under severe fault conditions, such as a major short-circuit, a circuit breaker can allow full prospective fault current to flow until interruption is achieved several cycles later.

In contrast to non current-limiting devices, a h.b.c. fuse interrupts a short circuit current at a value usually well below the peak value of the first loop of the prospective current and in a time equivalent to only one half a loop of current or less, both the peak let-through current and the let-through energy (I^2t) are therefore reduced to a small fraction of that possible with a non current-limiting device

A typical example which highlights the difference in energy let-through is as follows: in an 11kV ring system having a fault level of 350 MVA, a circuit breaker would allow about 500 times more energy into the seat of the fault as compared with say a 63A rated h.b.c. fuse.

4.3.2 Fuse End Boxes (FEB's)

Another option which is being considered by REC's and other end users is the replacement of RMU's at non strategic points with FEB's. A Fused End Box takes advantage of the availability of the new Full Range type fuse-links. The FEB is simply an enclosure, housing a set of three full range fuses, which is attached to the side wall of the transformer. The transformer terminals are connected directly to the load side of the fuses with the ring main connected to the source side of the fuses. One typical arrangement, is shown in figure 16. There are obviously numerous arrangements one other example would be to also put a switch in the tee-off which would ensure less consumers would be lost if one transformer with an FEB had to be worked on.

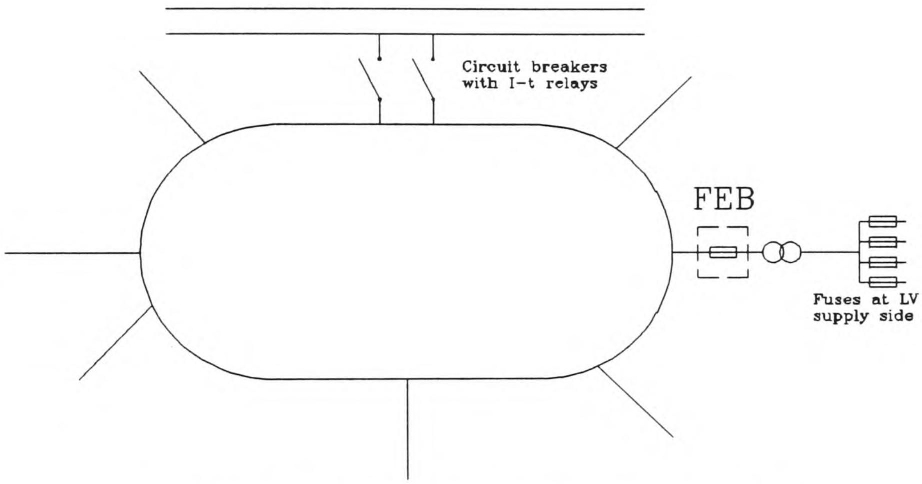


Figure 16 A tee-off arrangement using FEB's

Using FEB's in the distribution network would ensure that current limiting and overload protection of the transformer is maintained. Another major advantage is in the cost of equipment as an FEB and full set of full range fuses costs a fraction of the price of alternative protection.

However, with FEB's, switching facilities are no longer available which cuts down on the fault isolation available for repair & replacement of fuses. Also, three phase switching in the event of a single phase fault is no longer possible. However this can be considered an advantage (depending upon the policy of the utility) as supply will be maintained on the other phases when one phase only becomes faulty, ensuring disruption of supply to a smaller amount of people.

The Fused End Box, with the integral Full Range fuse, therefore offers the possibility of an alternative option to the RMU's in locations where the desirability of having switching facilities is outweighed by economic considerations.

4.4 Summary

There has been a developing trend towards the use of circuit breakers in protection systems rather than the traditional RMU's. However, there are distinct advantages of h.b.c. fuse-links over alternative non current-limiting devices such as circuit breakers, that is, both peak let-through current and let-through energy (I^2t) are reduced to a small fraction of that possible with a non current-limiting device.

The concept of full range fuses promises a greatly enhanced degree of protection for distribution systems in general and offers possibilities for both simplifying and improving the protection arrangements for future distribution networks.

Where switching is not considered necessary, the full range fuse-link offers the possibility of an alternative approach for transformer protection since the fuse is able to function with complete safety at all values of overcurrent without the aid of striker-tripped opening of an associated fuse switch, thereby offering savings in the capital cost of providing an effective degree of system protection on future networks.

Consultation between interested users and equipment manufacturers will ensure that FEB's meet specific user requirements. One thing that is certain is that the market requires full range fuse-links to meet certain international standards for transformer protection. Therefore for the 'Fullran' fuse to succeed in this potentially lucrative market, the operating characteristics need to be suitably altered to meet market demand and satisfy the customer.

5. The Development of the 'Fullran' Full Range Fuse-link 6.3 - 40 A Range

Fullran full range fuse-links with rated currents of 6.3 - 40 A, have all the parallel fuse-strips attached to one supporting quartz tube. For rated currents of 50 - 80 A, the fuse-element consists of a greater number of parallel strips attached to two concentric quartz tubes. The various ratings within both these ranges only differ in the thickness of the fuse-strips and hence in their resistance value.

It was decided to concentrate the initial development work on the 6.3 - 40 A range that encompasses the majority of the complete range and has the simple single quartz tube construction.

5.1 Conventional 6.3 - 40 A Fullran Element Design

From figure 17, it can be seen that the element design for this particular range of fuse-links consists of 15 notched elements connected in parallel. All the notches are of equal length and equally spaced along the length of each strip. The M-effect 'tin-spot' is situated at the centre of each strip (approximately 1 mm away from a notch).

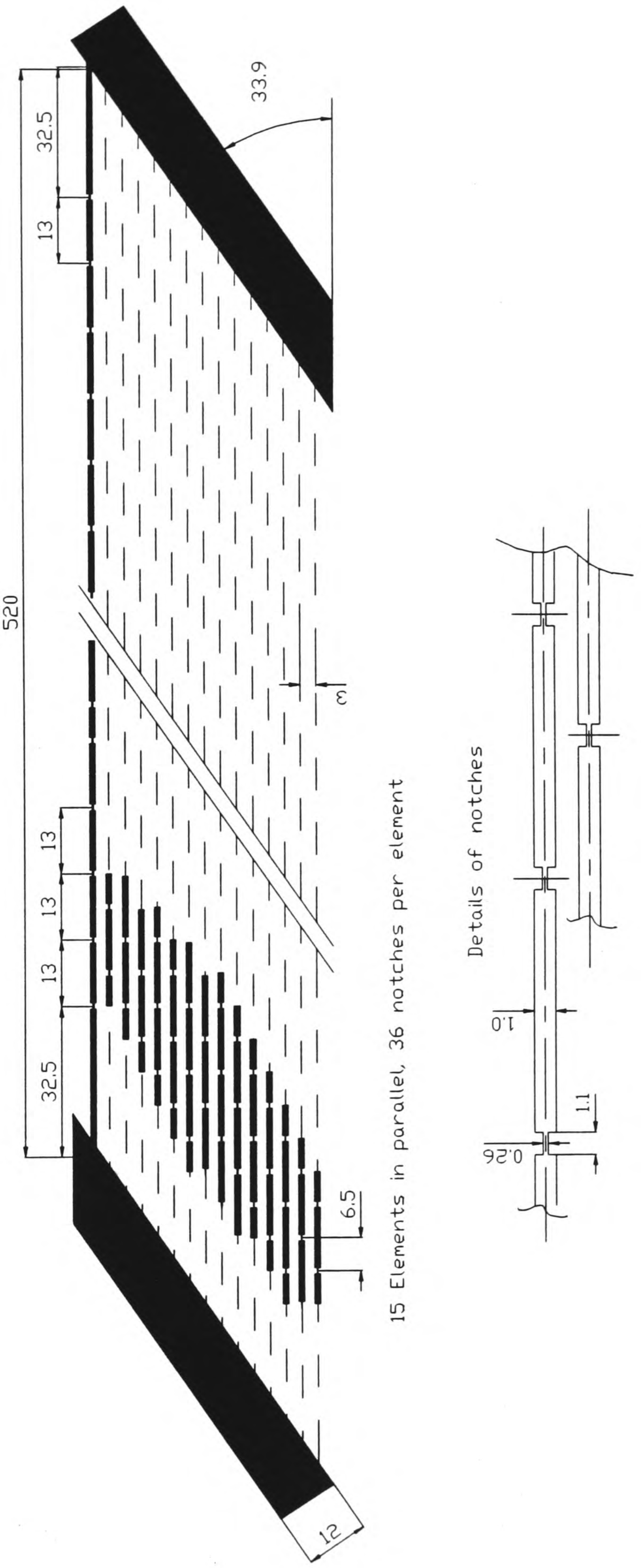


Figure 17 Element details of the Fullran 6.3 - 40 A range of fuse-links

The Fullran operating characteristics fail to comply with application standards due to the 'belly' in the centre region of the time / current curve. There are two areas in the operation of the fuse that need consideration in order to eliminate this belly.

The first area is prior to M-effect operation, that is operating times of approximately 1 second or less. This is the zone where melting is initiated in the notched sections of the fuse element. [23]

The second region is when the M-effect comes into play that is operating times of approximately 1 second or above. [23]

The obvious way to change the operating characteristic of any fuse-links is to modify the element pattern in some way. Due to the nature of the Fullran manufacturing process, the element patterns of these fuse-links can be easily modified by altering the pattern on the printing screen. Different notch profiles can also be introduced at set locations, the spacing and length of the elements can be easily and accurately altered etc.

The printing process therefore enables the development of many different types of design that could achieve the required improvement in operating characteristic.

Although the element can be easily modified, and hence the time / current curve tailored to meet required specifications, the fuse must also comply with stringent breaking capacity requirements. A trade off therefore invariably exists between time / current curve design and breaking capacity requirements.

5.2 The 'G' Design Element Modification

In order to try and eliminate the belly in the Fullran characteristic and hence produce a more marketable fuse, Holec did some initial development work in the late 1980's.

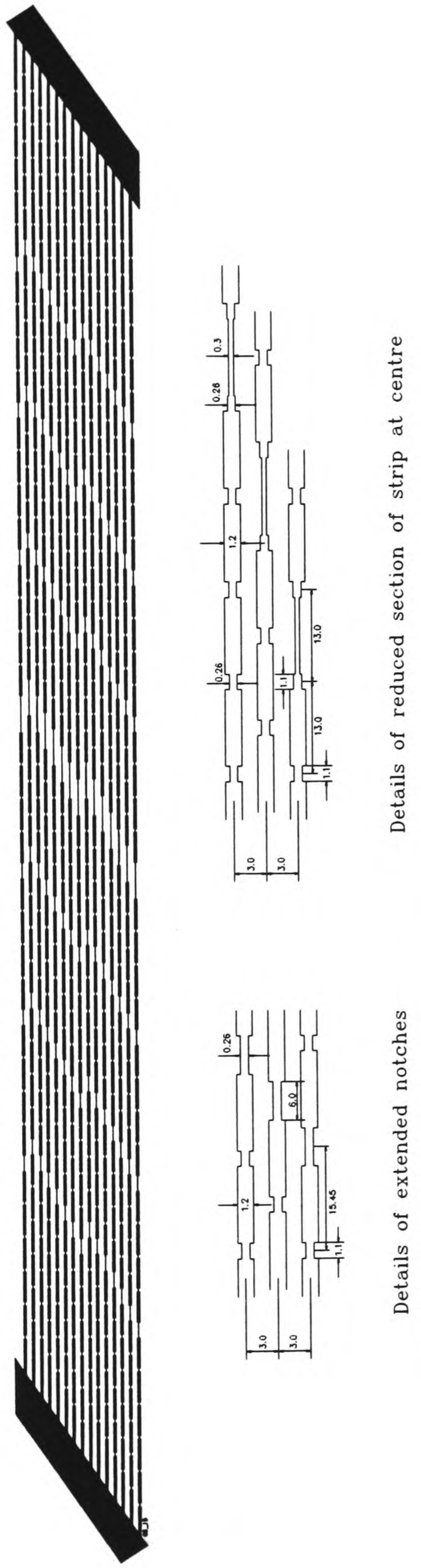


Figure 18 The G6-15 element pattern

The design that Holec produced was advanced at B & S Fuses by the author and the element design known as the G6-15 element pattern was developed (figure 18).

The design has two distinct differences, when compared with the conventional element pattern, that enables an improvement in operating characteristics to be achieved.

The first difference is in the introduction of 6 extended notches (restrictions) evenly spaced between the standard notches (figure 18). The second is the introduction of a thinner section of strip at the centre of the pattern with the tin-spot situated at the centre of this strip (figure 18).

Holec had proved through experimental work that in order for the fuse characteristic to be altered sufficiently to meet the relevant operating standards at least 6 extended notches needed to be introduced into the design. These notches were 6 mm in length as opposed to the regular length of 1.1mm. This modification had the effect of speeding up the operation in the region prior to the M-effect taking place.

In order to speed up the operation after the M-effect, Holec concluded that the M-effect alloy needed to be placed in the centre of a restricted section of strip which would be running at a higher temperature than the main body of the fuse element due to its greater current density. The length of strip was also found to be crucial in the design as the longer the strip the greater the heat would be at its centre, when operating for long pre-arcing times (due to the extended distance of the 'heat sink' of the main element from the centre of the restricted section of strip and hence the M-effect material). The experimental work undertaken proved that a length of 13mm was sufficient to produce the required modification in operating characteristic.

A more detailed description on the theory of how these modifications improve the time current characteristics of the design is given in the next section.

5.2.1 Theory of Operation of the G6 Designs

In the region of operation < 1 ms the operation can be considered adiabatic (no heat losses) and therefore melting of the elements will be initiated in the area of greatest current density. In the case of the conventional Fullran design and this modified 'G6' design the greatest current density is at the centre of the notches, therefore melting is initiated at these locations. The cross sectional area of the notches is identical for the Fullran and G6 designs hence there will be no difference between the two time current characteristics in the adiabatic region.

For operating times greater than 1 ms and typically less than 1 second heat losses start to play a major part in the operation of the fuses. [23] Initially the major heat transfer is from the centre of the notches to the main part of the strip which has approximately three times the cross sectional area of the notch with the corresponding reduction in current density.

The extended notches of the G6 design are over five times as long as the regular notches and therefore heat transfer from its centre by conduction is considerably less than at a regular notch. This reduction in heat transfer ensures that initiation of arcing is transferred exclusively to the extended notches of the G6 design. The period between arc initiation at the extended notches and the regular notches increases with increasing values of pre-arcing time with a significant improvement to the time / current curve. This increase in the period can be explained due to heat losses increasing with time. As heat losses start to play a more important part in the operation of the fuse, the temperature differential between the centre of the short 1.1mm notches and the extended 6mm notches increases and consequently the period between arc initiation at the different length notches will also widen.

A low-melting-point-alloy, the tin-spot, is used at the middle section of the conventional Fullran fuse design to limit operating temperatures under low current operating conditions. This also affects the fuse operating characteristic for pre-arcing times greater than say 1 second. [16] The tin-spot on the G6 design is placed in the middle of a strip of reduced cross section situated at the centre of the element pattern. This reduced cross section ensures a greater current density in the region of the tinspot and hence a higher temperature at the tinspot. This therefore causes the M-effect to operate sooner than on the conventional design causing faster operation in the centre region of the time / current characteristic.

The 'G6' element design was a major design improvement as the operating characteristics of fuse-links using this element pass through the required operating 'gates'.

The effect of both the modifications can be seen in figure 19.

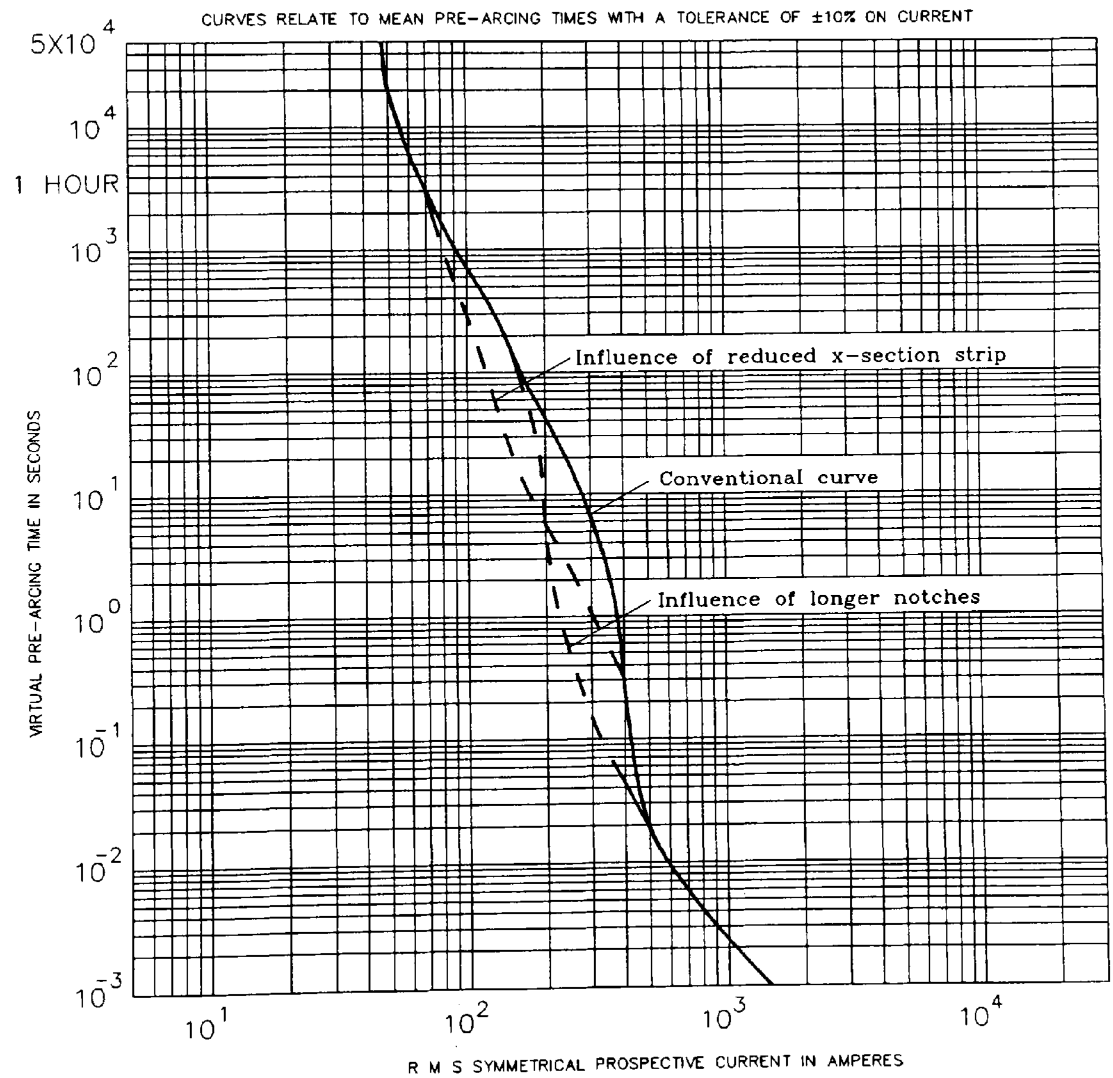


Figure 19 The effect of the 'G6' design modifications on the time/current characteristics of a 40 A Fullran fuse

5.3 Element Design Using a 'Multi-Element Bridge'

The process of screen printing the fuse elements onto a supporting tube opens the way for design concepts that would be totally impossible with traditional manufacturing methods. During the teaching company programme a whole new concept in fuse design was jointly conceived and developed by the author and Managing Director at B & S Fuses which took fuse element design into completely new territory.

As was shown in the 'G6' type design the time / current characteristics were altered by elongating notches (the areas with highest current density) and changing the current density of the strip where the tinspot is located. These changes in element design could possibly be achieved using traditional techniques of punching silver ribbon. However, the new concept devised during the teaching company programme took element design into areas which could never have been investigated using traditional methods of manufacture. The idea involved merging fuse elements over a set length to produce a 'multi-element bridge' configuration.

5.3.1 Design Theory

From the profile of a conventional 40 A Fullran notch (figure 20) it can be seen that the width of the strip is just over three times the width of a single notch. Therefore, if three elements were to merge for a time along a section of strip (figure 20), there would be a similar current density in the formed bridge as in the notches.

The extra length of the bridge, compared with the notches, would give the same effect as the elongated notches of the G6 design. That is, the heat transfer from its centre by conduction would be considerably less than at a regular notch ensuring faster operation in the period just after heat losses start to play a part.

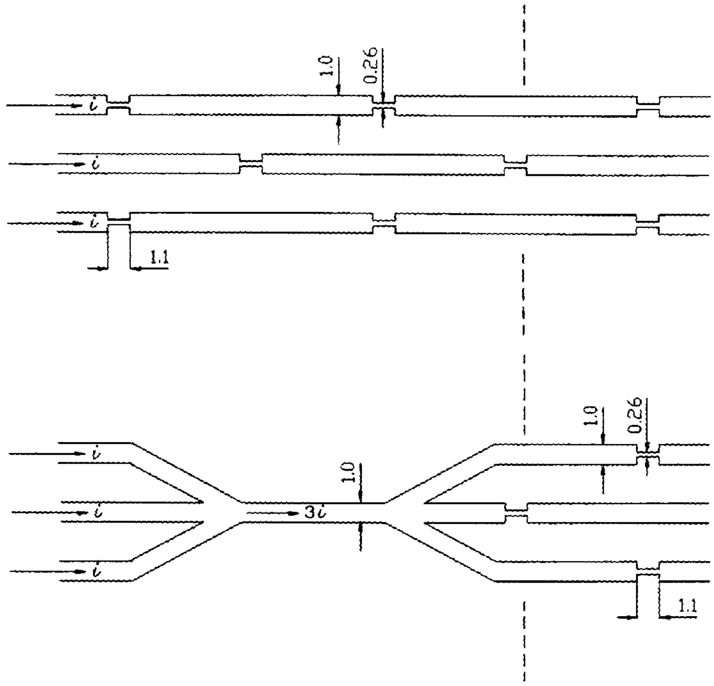


Figure 20 Notch profile of conventional Fullran design, and merging of strip sections (showing increase in current density)

The effect of heat losses to the silica quartz tube need also to be considered. It has been shown with the aid of liquid crystal thermography and infra-red radiometry, that when a fuse element is printed onto a silica substrate, there is significant heat loss from the fuse element to the substrate which therefore slows down the operation of the fuse [24]. Obviously, the larger the surface area of the element in contact with the quartz tube the greater the effect of the heat losses to this media. However, it was felt that the slight increase in the surface area in contact with the quartz tube in this bridge design would not have too much of a negative effect in the predicted improvement in operating performance.

Locating the tinspot at the centre of this bridge would also have the same effect as placing it on a reduced section of band in the G6 design, giving an improvement in the >1 second region.

Another envisaged advantage would be in the arcing performance of the fuse under low fault current operating conditions. With the conventional multi-parallel element configuration each element has to melt, at either the tin-spot or a notched section in all the elements before commencement of arcing. Commutation of the arc (transfer of the arc from element to element) then occurs between elements at random until the final element develops sufficient arc-voltage to suppress the current [8].

Commutation of the arc under a low overload fault current can be further explained by looking at the process a fuse goes through to break a low fault current. Taking the original 15 element Fullran fuse as an example with rated current of In. The design has 15 parallel fuse elements with each element dimensioned for 1/15.In (=In'). If an overload of 2.In flows through the fuse-link, then each element, assuming that no melting has yet taken place, will conduct a current of 2.In'. Whenever one of the fuse elements melts, the current is taken over by the remaining elements. When five of the elements have melted the current in each of the remaining elements will have increased to 3.In'. Finally, only one of the elements will conduct the total current of 30.In'. this last element will not fuse at the M-effect but at the notches due to the large current density and build up of temperature in the restrictions.

The result of this process is a rapidly increasing arc voltage. When the arc voltage has reached the flash-over voltage of a fuse element previously melted at the M-effect, this element takes over conducting the total current (30.In'). This element will also melt at its notches and in turn restrikes another previously melted strip. Through this process the current commutates until all the elements have melted at the notches. Finally, the last fuse element breaks the residual current.

Using a multi-element bridge configuration arcing would commence when one bridge in all element sets has melted. Commutation of the arc would then continue within one element set at the notched sections until it is forced to commutate to another element set. This 'dual step' commutation process continues until the final element set clears the current.

5.3.2 Design Alternatives

There are other factors apart from merging three elements which come into effect with the operation of the fuse (considering an element set consisting of a grouping of three elements with at least one bridge):

The location / number of bridges per element 'set' and the location / number of tinspots on these element sets. A number of alternative designs were looked at.

i. Locating one bridge per element set at the centre of the elements (figure 21)

ii. Locating one bridge per element set at the ends of the elements (figure 22)

iii. Locating two bridges per element set at both ends of the elements (figure 23)

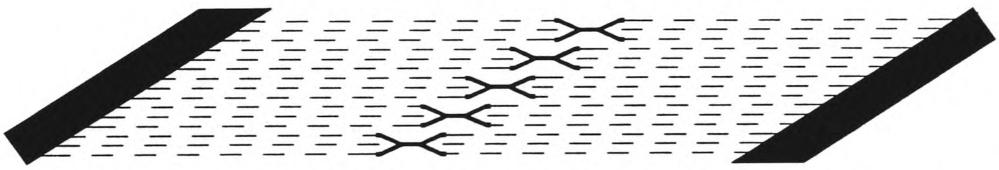


Figure 21 Locating one bridge per element set at the centre of the elements

The hottest part of the fuse during low overcurrent operation is the centre as it is the greatest distance away from the heat sinks of endcaps and terminal connections. Locating a bridge with tinspot in the centre of the pattern could therefore cause the fuse to operate too quickly for low overloads causing problems with discrimination and the assignment of current ratings. Option (i) was therefore rejected as a design possibility.

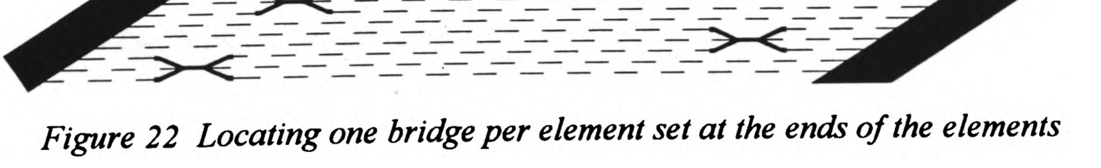


Figure 22 Locating one bridge per element set at the ends of the elements

Locating one bridge per set at the end of the elements would overcome the problem of the fuse operating too quickly over low overload fault conditions by moving the location of the tinspot away from the hottest area of the fuse. However the fuse design would be non-uniform with 2 bridges at one end and three at the other, therefore this option was also rejected as a design possibility.

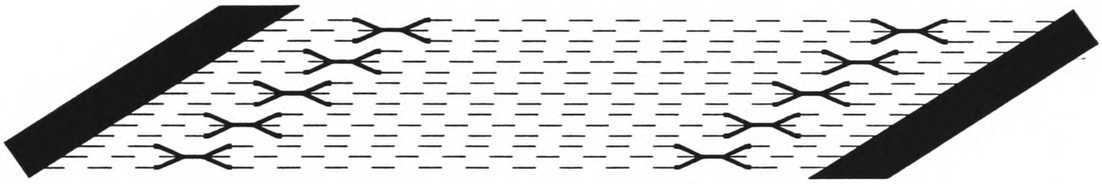


Figure 23 Locating two bridges per element set at both ends of the elements

Introducing bridges into both ends of the element pattern would overcome the problem with the fuse operating too quickly and would also produce a uniform element pattern. Therefore this was considered the preferred option.

Locating tinspots at the ends of the element pattern enables the notches at the centre of the fuse to be closer to their melting point upon commencement of arcing. This is known to assist the arc 'burn-back' process thereby aiding the arcing performance.

The question left to be answered is the number and location of the tinspots. There are two possible options: (a) putting a tinspot on every bridge; (b) putting a tinspot on only one bridge of each element set.

The advantage of putting a tinspot on each bridge would be that the fuse elements would be completely uniform. However, it was felt that the difference between the operation of the fuse with two or three tinspots at the top (when the fuse is mounted vertically) would be negligible; once the first two tinspots had melted, the current density in the other bridges would be increased by a factor of 5/3, the temperature of the remaining bridges would therefore very quickly reach the point of M-effect operation regardless of whether located top or bottom. Only one tinspot is actually necessary per element set as each set only needs to be broken in one location before arcing commences.

The advantages of putting the tinspot on only one bridge would be in the control of where arcing is initiated and the number of tinspotting operations necessary per fuse. It was decided that the best option between the two would be to locate the tinspots on one bridge only alternately on top and bottom.

5.3.3 Production of Prototypes

Initially to test out the basic design theory and its effect on the time / current characteristic, a number of conventional Fullran 40 A designs were modified. A photograph of one of these prototypes is shown in figure 24.

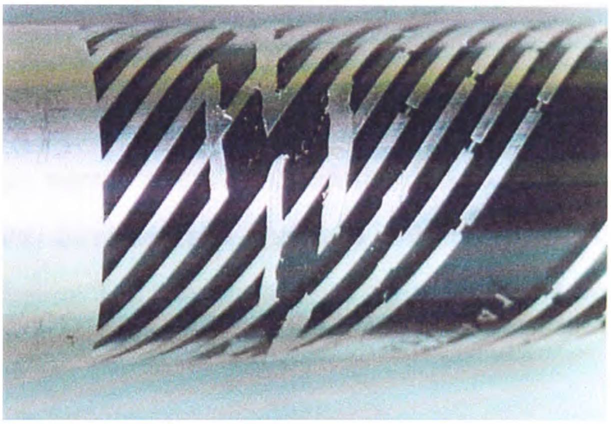


Figure 24 Photograph of an initial prototype of a 'Multi-Element Bridge' design

Figure 24 shows sets of three elements merging for a short distance (approximately 10 mm) and then branching out again into individual elements. The M-effect is located in the centre of the formed bridges on alternate sets; in the case of figure 24, the M-effect was located on the top bridge of the two that are clearly visible. A low overcurrent test has been carried out on this prototype and the element has been broken at the M-effect.

A number of these prototypes were tested in a low voltage (30V) laboratory test set to establish time / current points in the region where the operating time needed to be accelerated. The results achieved as shown in table 1.

Current (A)	Time (seconds)	
	Modified Elements	Standard Fullran Elements
70	3830	3000
120	240	800
170	7.2	100

Table 1 Time current test results for multi-element bridge prototypes

These values show that a significant improvement in operating time in the centre region of the characteristic was made by the introduction of the bridge. The operating time for the lower current value was also encouraging showing a comparable operating time to the conventional design. If this part of the characteristic also moved over to the left that is to say it operated much faster for the same prospective currents then the fuse would be too close to operating at its assigned rated current and therefore the design would not be practicable.

5.3.4 Production of the First Design

The success of these prototypes enabled a new element pattern to be designed utilising this bridge configuration.

The production of a new element design for Fullran fuses obviously requires a new printing screen to be made. The process of making a new screen begins with the production of an element pattern using a good CAD package.

The exact element design is first of all laid down using the CAD package. This screen design can then be converted to electronic data from which the print screen manufacturer can produce a photographic 'positive'. This positive is of extremely high accuracy and a print screen bearing the required element pattern can then be produced.

The ability to use CAD ensured that the designs were of a very high accuracy and also enabled various bridge designs to be designed and viewed on screen. As previously stated the merging of element to form a bridge is a totally new concept and therefore no design guidelines were available for review.

The original prototype formed the bridge by producing a path across the elements in parallel with the end collars. This design was used in the prototypes due to the ease of production. However, it was not considered suitable for a developed screen as it consisted of sharp corners which were adjacent to one another. The type of bridge chosen was a much 'smoother' design giving a more symmetrical appearance over the bridges. The bridge design is shown in figure 25.

The first 'bridge' design produced was known as the JP5-3 element pattern. In order to have the smallest number of unknowns, the design kept as many features as possible the same as for the conventional Fullran design.

The minimum distance between the collar and the beginning of a bridge was set at approximately half of one pitch (6.5 mm) in order to retain as many notches as possible (the short circuit performance of fuses improves as the number of notches increases, see section 5.5). The bridges were arranged so that the notches aligned as with the conventional design. The complete design details are given in figure 25.

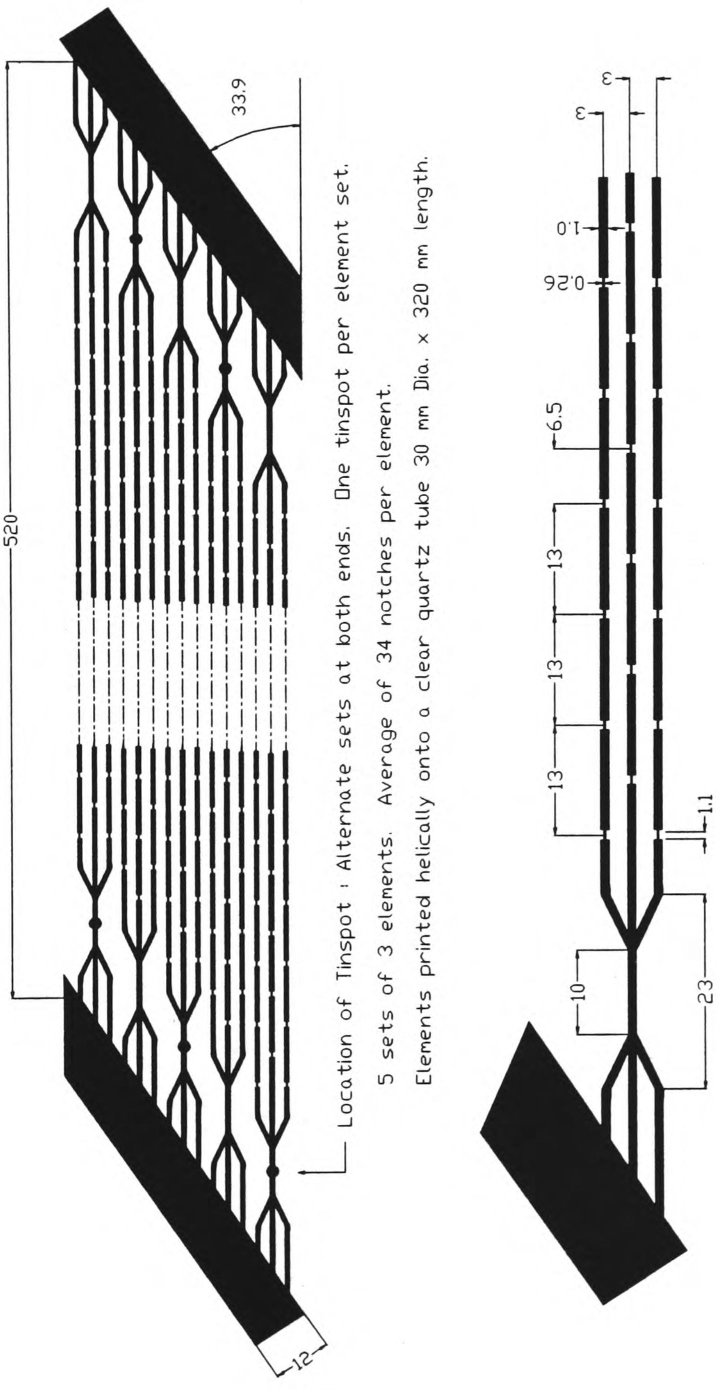


Figure 25 Multi-element bridge design and JP5-3 element details

5.4 Preliminary Type Testing of New Designs

5.4.1 Type Testing Requirements for IEC 282-1 Certification

IEC 282-1 states that fuse links are considered as forming a homogeneous series when their characteristic comply with the following 8 points [5] :

1. Rated voltage, breaking current and frequency shall be the same.
2. All materials shall be the same.
3. All dimensions of the fuse-link except the cross-section and the number of fuse element(s) as detailed below from items 4 to 8 shall be the same.
4. In any fuse-link, all the main fuse-elements shall be identical.
5. The law governing the variation of the cross-section of individual fuse-elements along their length shall be the same.
6. All variations in thickness, width and number shall be monotonous* with respect to rated current. Thus, balancing an increase in cross-section by reducing the number of fuse-elements and vice versa is not allowed.
7. The variation in distance, if any, between individual fuse-elements and that in distance, if any, between fuse-elements(s) and fuse-barrel shall be monotonous with respect to the rated current.
8. A special fuse-element used for an indicator or striker is exempt from Items 5 and 6 above, but this element shall be the same for all the fuse-links.

* Monotonous function: a function continually varying in the same direction for a given direction of the variable.

The Fullran 6.3 - 40 A range is considered as forming an homogeneous series as the characteristics comply with all the above Items.

Looking at the breaking test requirements for certification of a homogenous series of fuse-links as laid out in IEC 282-1:

Breaking tests need only be made in accordance with the following table (figure 26).

Symbols in the table are used with the following meanings:

A: fuse-link of lowest current rating

B: any fuse-link of a current rating between A and C.

C: fuse-link of highest current rating.

s: cross-section of the individual main fuse elements.

Test duties	Fuse-links to be tested (crosses show the tests to be performed)		
	A	B	C
1	X		X
2 (note 1)	X (note 3)		X
3 (note 2)	X (note 4)	X (note 4)	X

NOTES

1. The test currents I_2 for the fuse-links A and C will have been chosen according to the current rating of fuse-links A and C respectively.
2. The fuse-link of lowest current rating should contain at least two individual main fuse-elements in addition to the elements, if any, used for operating the striker.
3. This test is only required where the cross-section of individual elements is less than that for fuse-link C.
4. This test is only required when the ratio I_3/s of fuse-links A and B is less than that of fuse-link C. In this case, the fuse-link having the lowest ratio I_3/s shall be selected for test duty 3.

Figure 26 Table IV A, Section 13.3.2 Test Requirements, IEC 282-1:1994

Looking at the table in figure 26:

The test current denoted by I_2 in Note 1 is the Test Duty 2 current (critical current).

The test current denoted by I_3 in Note 4 is the Test Duty 3 current (minimum breaking current). Applying Note 4 to the Fullran range of fuses tested at rated current for full range performance we get:

	Current Rating (A)	Thickness of Strip (μm)	Width of Strip (mm)	I_3/s (A/mm^2)
A	6.3	5	1	1260
B	16	14	1.01	1142
C	40	38	1.05	1002

Table 2 Ratio of current rating to element cross section for Fullran fuses

As shown the 40 A fuse has the lowest ratio of I_3/s and hence only this rating needs to be tested for Test Duty 3 performance. Therefore to satisfy the breaking test needs for certification to IEC 282-1 for the newly developed 6.3 - 40 A range the following tests must be performed:

Test Duty 1 3 tests of the 6.3 A fuse-link and 3 tests of the 40 A fuse-link

Test Duty 2 3 tests of the 6.3 A fuse-link and 3 tests of the 40 A fuse-link

Test Duty 3 2 tests of the 40 A fuse-link

5.4.1.1 Breaking Tests

The three breaking tests (Test Duties 1, 2 & 3) give the most severe breaking conditions throughout the range of operating currents:

Test duty 1: Verification of operation with the rated maximum breaking current I_1.

Test duty 2: Verification of the operation with prospective current I_2 at which current limitation occurs when a high level of energy is stored in the inductance of the circuit. This test is often referred to as the critical current test as the energy levels are generally at their maximum value at this fault current.

Test duty 3: Verification of operation with the current I_3: for General Purpose fuses, this is the rated current that causes melting in 1 hour or more; for Back-Up fuses, it is the rated minimum breaking current. For full range fuses an alternative test method can be carried out as detailed in chapter *2.2 'Testing for Full Range Capabilities'*.

5.4.2 Initial Development / Testing Shots

Before the big outlay involved in booking a test station for full certification (such as KEMA in the Netherlands) it was decided to perform some development tests on the new designs. Testing based on the certification requirements detailed in section 5.4.1 was undertaken at the Holec testing laboratories in the Netherlands in order to assess the technology and suitability of the new designs.

The fuses taken for test were 40 A ratings of each type of design. A comparison of the different element details is shown in table 3.

	Conventional Fullran	G6-15	JP5-3
No. of elements	15	15	15
Length of Elements	520 mm	520 mm	520 mm
Nominal Resistance	24 mΩ	24 mΩ	24 mΩ
Deposit	38 μm	38 μm	38 μm
Width of Strip	1.05 mm	1.05 mm	1.05 mm
Length of Notch	1.1 mm	1.1 mm & 6 mm	1.1 mm
Notch Width	0.31 mm	0.31 mm	0.31 mm
Number of Notches per element	36	28 x 1.1 mm 6 x 6 mm	Average of 34.5 notches per element over complete design

Table 3 Comparison of conventional, G6-15 and JP5-3 Fullran fuses

5.4.2.1 Test Results

Non-striker versions of the 40 A fuses were tested at Holec's Laboratories to TD2 & TD3 test specifications. These tests are generally the two most onerous tests out of the three and would therefore give a clear indication of the performance of the new designs.

Table 4 shows a summary of the results of the tests. The arc voltage indicated for Test Duty 2 tests is the instantaneous value of the voltage which appears across the terminals of the fuse during the arcing time. The figures quoted for the arc voltage are the maximum peak values.

The term 'OK' in the remarks column is used to signify that the fuse tested complied with the following requirements given in IEC 282-1 [5] relating to the behaviour of fuses under test:

a) A powder-filled fuse-link shall not emit flame or powder, although a minor emission of flame from a striker or indicating device is permissible, provided this does not cause breakdown or significant electrical leakage to earth.

b) After the fuse has operated, the components of the fuse, apart from those intended to be replaced after each operation, shall be in the original state. It shall be possible to remove the fuse-link in one piece after operation.

Fuse Type	Test Duty	Test Current	Test Voltage (kV)	Arc Voltage (kV)	Arcing Time (ms)	Remarks
G6-15	2	1.4 kA	10.4	21.4	5.8	OK
P321a	2	1.4 kA	10.4	20.6	6.0	OK
40 A	2	1.4 kA	10.4	18.9	5.3	OK
	3	40 A	12		274	OK
	3	40 A	12		253	OK
JP5-3	2	1.4 kA	10.4	20.8	6.5	OK
P321a	2	1.65 kA	10.4	19.9	6.8	OK
40 A	2	1.65 kA	10.4	21.8	5.8	OK
	3	40 A	12		385	OK
	3	40 A	12		314	OK
	3	33 A	12		446	OK * I_3 current below*
	3	33 A	12		426	OK * Rated Current *

Table 4 Test duties 2 & 3 development test results for G6-15 and JP5-3 Fullran fuses

5.4.2.2 Analysis of Test Results

The results of the tests, as shown in table 4, show that both of the new designs passed the Test Duty 2 shots successfully. The maximum permissible arc-voltage for 12kV rated fuse-links, as stated in IEC 282-1 [5], is 38kV. Table 4 shows that the maximum value of arc-voltage recorded for these fuses under test duty 2 conditions was 21.4kV for the G6-15 design and 21.8kV for the JP5-3 design. Therefore, the value of arc-voltage being produced by these two designs under test duty 2 conditions is approximately 57% of the allowable upper limit. The maximum arcing time for the two designs was recorded as 6.0 ms for the G6-15 design and 6.8ms for the JP5-3 design. Therefore, the current is successfully being extinguished in less than one half cycle.

Both the designs were also able to clear the Test Duty 3 (Full Range) shots successfully. They were able to clear the 40A 'fault' current, after arcing had been initiated, without any restrikes or external damage to the fuse-link. The JP5-3 design was also tested at a current level below rated current (33A). Asking the fuse to clear a current below its rated current after arcing has initiated is a more difficult test as the amount of energy going into the process of building up fulgurite and hence resistance to current is reduced. The results of table 4 show that the design was still able to pass this more difficult test.

Figures 27 and 28 show test oscillograms from TD2 critical current tests on G6-15 and JP5-3 respectively. In both cases, the top trace shows the current flow through the fuse and the bottom trace the voltage across the fuse.

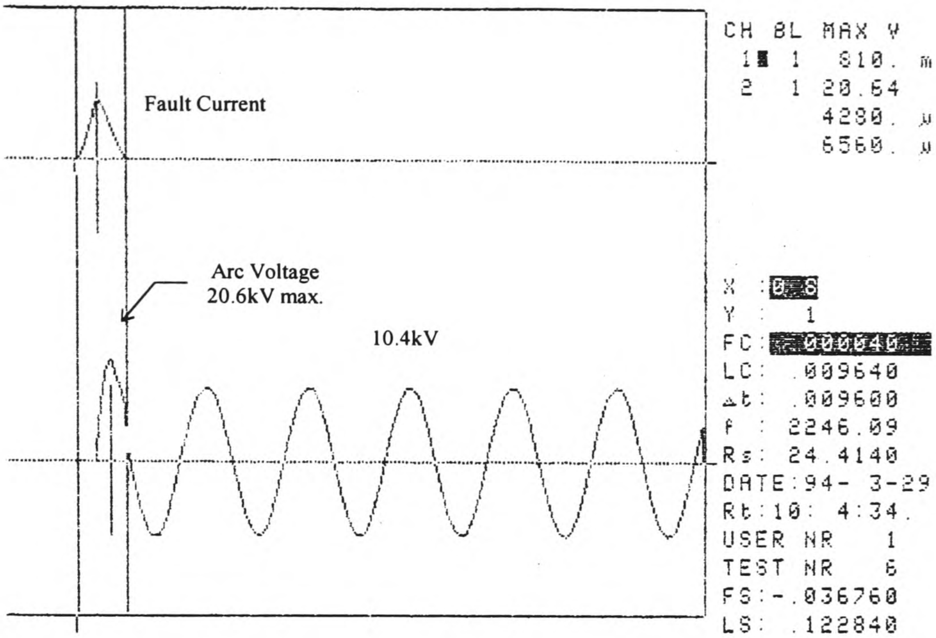


Figure 27 Oscillogram of the operation of a 40 A fuse with G6-15 element pattern under Test Duty 2 conditions to IEC 282-1

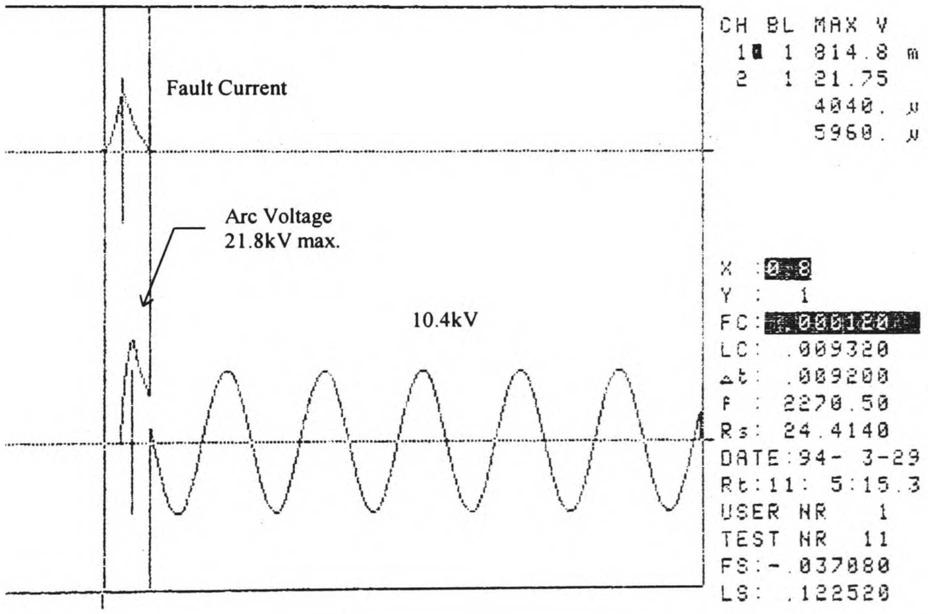


Figure 28 Oscillogram of the operation of a 40 A fuse with JP5-3 element pattern under Test Duty 2 conditions to IEC 282-1

Figures 29 and 30 show the test oscillograms from TD3 full range tests on G6-15 and JP5-3 respectively. In both cases, the top trace shows the current flow through the fuse and the bottom trace the voltage across the fuse.

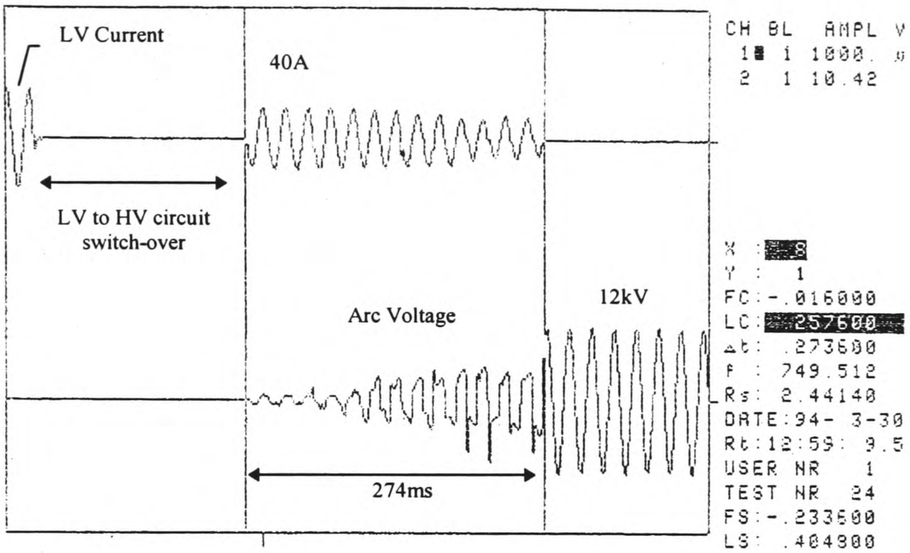


Figure 29 Oscillogram of the operation of a 40 A fuse with G6-15 element pattern under Test Duty 3 conditions to IEC 282-1

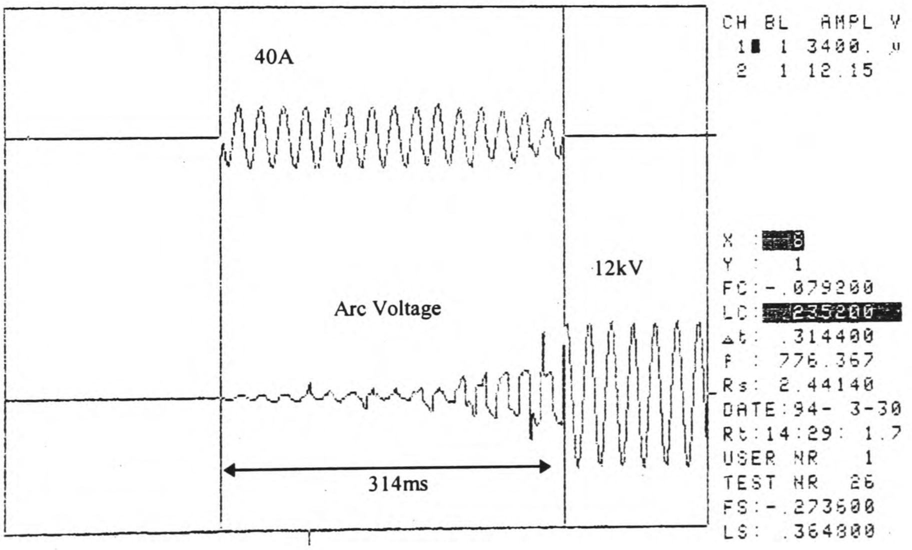


Figure 30 Oscillogram of the operation of a 40 A fuse with JP5-3 element pattern under Test Duty 3 conditions to IEC 282-1

With regards to the Test Duty 2 results of the two designs of fuse-link. Looking at the oscillograms of figures 27 and 28, in both cases the top trace shows the fault current being 'driven' down to zero in less than one half of a cycle. The bottom trace shows the voltage across the terminals of the fuses. This voltage rises to its peak value (the arc-voltage) before reaching its steady recovery voltage value of 10.4kV. The voltage is maintained across the terminals of the fuse for a period not less than 60 seconds for test duty 2 tests during which time the fuse-link must remain intact and the current extinguished.

Comparing the traces of the two oscillograms and the figures for the arc voltage and arcing time of the G6-15 and JP5-3 designs under Test Duty 2 conditions, given in table 4, it can be seen that the performances of the two designs under the critical current tests were comparable. Both designs were able to clear the fault current within a half of one cycle without any apparent stress and fully complied with the requirements of IEC 282-1 in respect of the condition of the fuse-links after the test.

With regards to the Test Duty 3 results. Looking at the oscillograms in figures 29 and 30, the top traces show the HV current flowing through the fuse after arcing has been initiated by the higher LV current (figure 29 shows the period during the switch-over of the two circuits). The bottom trace shows the voltage across the terminals of the fuse which builds up until the current is unable to be maintained and the arcing is extinguished. The recovery voltage which is 12kV for the test duty 3 shots is again maintained for a period not less than 60 seconds during which time the fuse-link must remain intact and the current extinguished.

It can be seen from the results of table 4 that again the two designs had a similar performance and cleared the fault without any apparent trouble. The arcing time for the JP5-3 designs does appear to be slightly longer than for the G6-15 design, however, when comparing the two oscillograms in figures 29 and 30, the arcing appears to be more controlled on the JP design with the arc voltage gradually building up until the arcing is completed. The G6 design whilst also successfully passing the full range test, shows a slightly more erratic arcing characteristic.

Considerable information on fuse performance can be obtained by opening and examining operated fuses. Upon examination of the fuses tested under critical current conditions, it was observed that a transfer of current between elements appeared to take place during fuse operation. This apparent transfer resulted in an excessive build up of fulgurite at both ends of the quartz tube. Fulgurite is the percentage of the filler material that is melted during arcing and then subsequently hardens. Any build up of fulgurite is a cause for concern as unusually excessive build up could reach the porcelain body causing it to fracture, resulting in catastrophic failure.

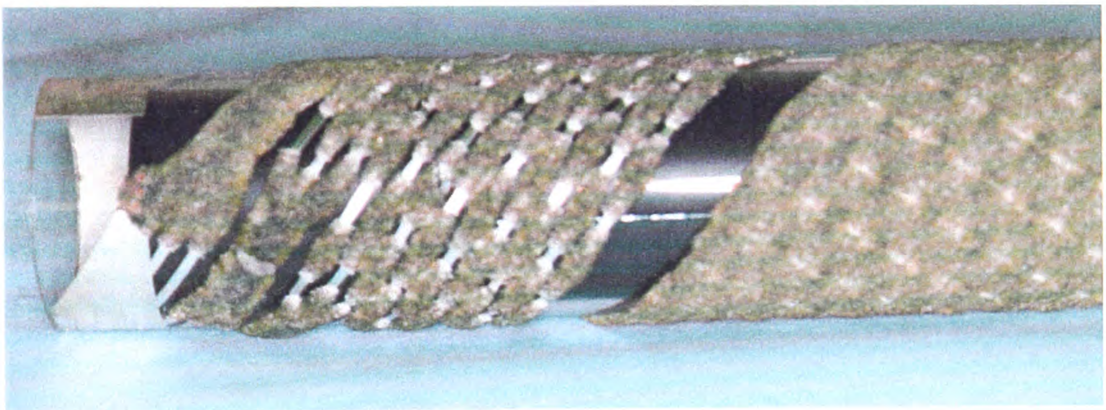


Figure 31 Photograph showing excessive build up of fulgurite due to current transfer (fuse tested under critical current TD2 conditions)

This apparent current transfer was observed on both the new designs and also on the conventional Fullran design which was tested for reference purposes.

Other technical performance parameters of the two new designs compared with the conventional Fullran design were:

- The power dissipation of the fuse is identical to the conventional Fullran design.
- For melting times < 1 ms the I^2t values are equal to those of the conventional design. For melting times > 1 ms the I^2t values are lower.
- The cut-off currents are the same as for the conventional design .

5.4.2.3 Conclusions From the Tests

After all the analyses it was decided to further develop the designs incorporating the element bridge in preference to the 'G' designs. The reasoning behind this choice was as follows:

- The very important fact that this element pattern lends itself more easily to production and in-process inspection than the G6-15 design.
- The more controlled arcing during TD3 shots.
- The comparable performance under TD2 conditions.
- Further supplementary tests also proved that higher current ratings could be achieved using the 'bridge' designs rather than the 'G' designs.

5.5 Further Development of The Multi-Element Bridge Design

The theory of the multi-element bridge was proved with the testing carried out on the JP5-3 design. Low voltage laboratory tests showed that the time/current characteristic was modified in the desired way. The high voltage short circuit tests showed that the design could pass TD2 & TD3 shots. However, there were aspects of the design and its performance that were concerning and important enough to justify further development work and modification. Also now that the bridge configuration had been fully tested there was the possibility of introducing other possible improvements into the element design.

The most concerning aspect of the performance was the transfer of current between elements during arcing. This transfer takes place when the fulgurite growth starts to merge between the elements during the arcing process. One way to overcome the transfer is to increase the gaps between the elements which produces a bigger non-conducting barrier for the current / fulgurite to breach. Any increase in spacing has to be at the expense of either the number of elements or the length of the elements.

The nature of the bridge design means that the number of elements would have to be decreased by three (one set) if any were to be sacrificed at all. This would mean that remaining elements would have to be plated much thicker in order to achieve the same resistance and current rating. It would also make the full range tests more difficult due to the larger cross sectional area of the element notches and hence a smaller current density being present in the notches during the arcing period. Due to these two factors, this option was dismissed.

Fuses are extremely voltage sensitive during the operating period [25, 26]. The arc is the manifestation of the stored energy in the circuit plus the energy derived from the system voltage. In order for the arc to be successfully suppressed the fuse must be able to build up enough resistance so that the system voltage cannot maintain the arc. Resistance to current flow is built up as the notches melt along the fuse elements. Due to this, the element length and the number of notches present is very critical, i.e. if the length is too short not enough resistance will be built up and the fuse will fail to drive the current down to zero resulting in a failure to clear the fault.

As fuses are so sensitive to voltage (with respect to the length of element necessary for their voltage rating) any reduction in length would have to be kept to a minimum, the amount of reduction practically available would depend upon the safety margin built in to the original designs i.e. the amount that the designs have 'in hand'.

The current transfer was a definite problem which needed to be avoided or at least minimised. It was therefore decided to strike a compromise between the need to introduce extra spacing between elements and the need to maintain element length.

5.5.1 Introduction of 'Arc Breaks'

A reduction in element length from 520 mm down to 500 mm enables an extra 3 mm of gap to be introduced into the element pattern. If the 3 mm were evenly distributed between all the element spacing, the effect would be negligible. Therefore extra spacing needs to be introduced in significant amounts at fewer places. In order that the design stayed somewhat symmetrical it was decided to introduce an extra 1.5 mm gap either side of the middle set to give a total break of 3.5 mm between the outer elements of the sets. These so called 'arc breaks' should ensure a more evenly distributed current path at each end of the element.

5.5.2 Alternate Long / Short Notches

Another design feature which has proved to be successful in previous designs is alternate long and short notches with a smaller pitch. In this context the 'long' would be standard length notches, 1.1 mm, and the 'short' would be 0.6 mm. This long / short combination has been shown to improve the arcing performance of fuses (on the conventional Fullran 50 - 80 A range). This combination enables more notches to be introduced into the design which means a greater number of melting points along the length of the elements and hence quicker build up of dielectric strength. [27, 28]

However, there is a limit to how many notches can be introduced into a design. This is due to the increase in resistance as more restrictions are introduced which would ultimately mean that higher ratings are impossible to achieve. In the case of this design the increase in resistance due to the increase in notches is offset by the reduction in overall element length (which obviously reduces the resistance).

After proving that the bridge does have the desired effect of taking the 'belly' out of the time / current curve, these other modifications can be introduced without having too many unknowns in the design at once.

5.5.3 Position of the Bridges

The size and shape of the bridges looked to be of the right order upon inspection of the tested fuses. The only question mark was in the positioning of these bridges with respect to the end collars.

After inspection of the tested fuses it could be seen that the areas of greatest fulgurite growth were at the bridges where the elements merge. When all the silver has been consumed at this point, the arcs 'burn-back' along the elements. It was observed that the elements were burning back right the way to the end collars on the tube. If the arcing and fulgurite growth became too severe or the element burnt back a bit more, i.e. right to the end caps, it could damage the integrity of the fuse resulting in catastrophic failure.

To overcome this potential problem, the initial length of element before the beginning of the bridge can be increased taking the high fulgurite growth areas at the bridges further away from the end collars.

5.5.4 The Modified Design 'JP5-3R1'

Incorporating all the discussed points, the modified design included the following new features.

- Element was reduced from 520 mm to 500 mm
- Two 'arc breaks' of 1.5 mm introduced either side of the middle element set to give a 2-1-2 type configuration.
- The number of notches increased from 36 to 50 by the introduction of a smaller pitch (13 mm down to 8.2 mm) and alternate 'long' (1.1 mm) / 'short' (0.6 mm) notches.
- The initial length of element before the beginning of the bridge was increase in order to take the high fulgurite growth areas at the bridges further away from the end collars to avoid possible problems with 'burn-back' .

Details of the modified design are shown in figure 32.

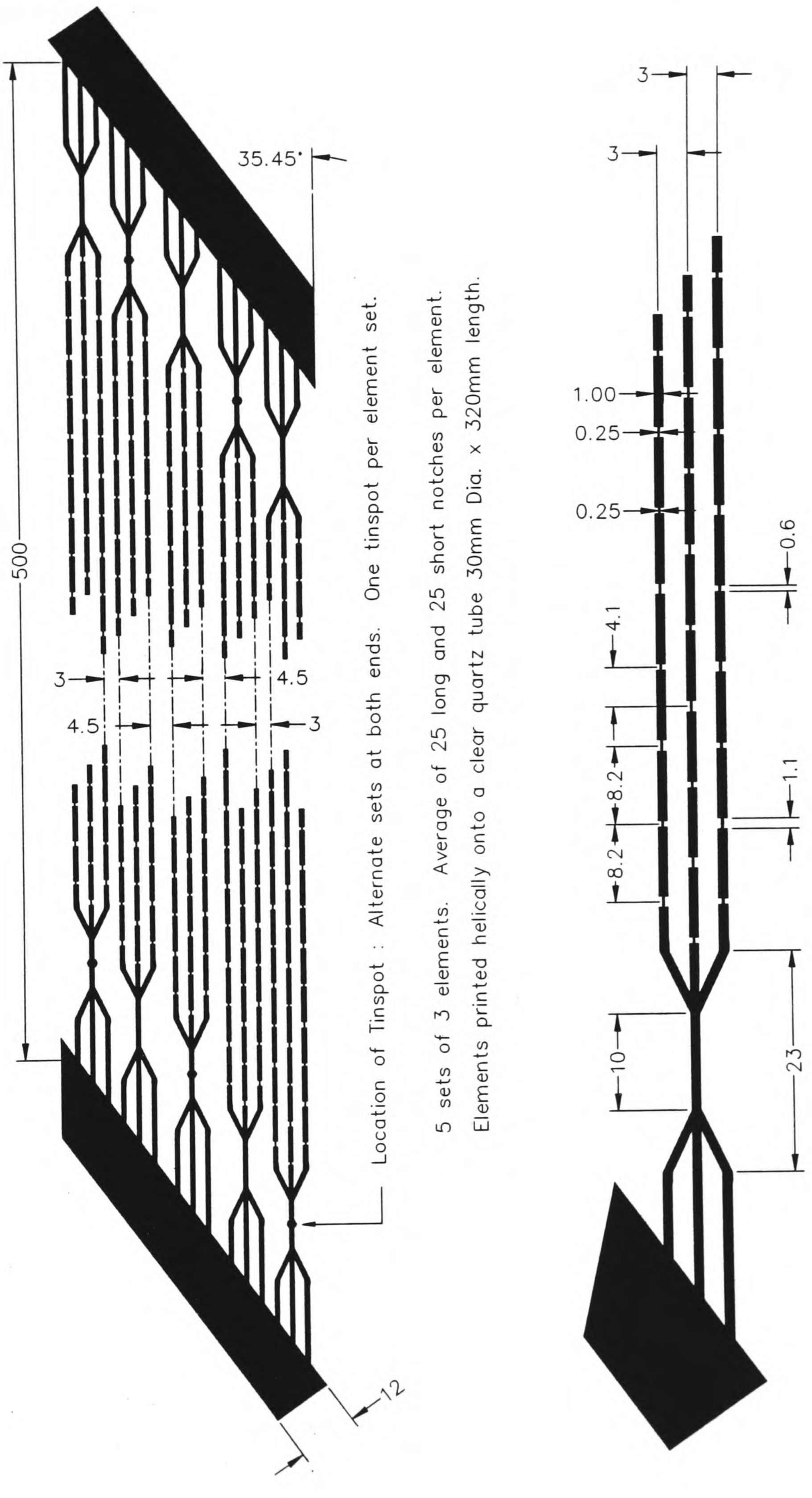


Figure 32 The details of the JP5-3R1 element design

The results from the first series of tests combined with the improvements made to the design gave enough encouragement and confidence to take this new design forward for full certification to IEC 282-1.

5.6 Certification of 6.3 - 40 A Range to IEC 282-1

Two 6.3 - 40 A designs were taken to test as a safeguard against unexpected failure. The modified design with JP5-3R1 element and the original development design with JP5-3 element.

The certification testing was to carried out at the KEMA Short Circuit Test Stations. Due to the high cost of the test station it was decided to initially certify the fuses as 'Back-Up' class fuse links. The certificate could then be supplemented by a report of performance with full range TD3 tests carried out in the Holec Laboratories and witnessed by a KEMA observer.

5.6.1 Type Test Results

KEMA Test Station IV				
Fuse Type	**Test Duty**	**Test Current**	**Test Voltage (kV)**	**Remarks**
PP321a JP5-3R1 Element 40 A 12 kV	1	40 kA	10.8	OK
	1	40 kA	10.8	OK
	1	40 kA	10.8	OK
	2	1.64 kA	10.8	OK
	2	1.64 kA	10.8	OK
	2	1.64 kA	10.8	OK
	3	187 A	12.0	OK
	3	187 A	12.0	OK
PP321a JP5-3R1 Element 6.3 A 12 kV	1	40 kA	10.8	OK
	1	40 kA	10.8	OK
	1	40 kA	10.8	OK
	2	255 A	12.0	OK
	2	255 A	12.0	OK
	2	255 A	12.0	OK

Table 5 Certification type test results for 6.3 - 40 A Fullran fuses using JP5-3R1 element design (for Back-Up performance)

At this stage the 6.3 - 40 A homogeneous range had passed all the type test necessary for Back-Up classification. Another test which has to be carried out by the testing station is the temperature rise test.

The temperature rise test consists of mounting the highest rated fuse in the series, in this case 40 A, in its most unfavourable position (in this case mounted vertically). A current equal to its specified rated current is then applied to the fuse until the temperature of all parts become steady. There are definitive values laid down in IEC

282-1 giving maximum permissible temperature and temperature rises and these parameters must be met by the tested fuse-link [5]. Figure 33 shows a schematic diagram of the set up for temperature rise tests.

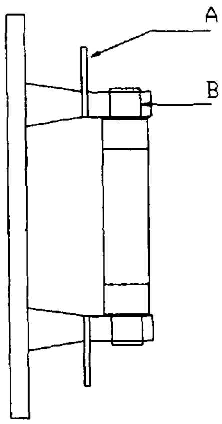


Figure 33 Schematic of the set up for temperature rise tests

Once this temperature rise test had been successfully completed and the construction of the tested fuse-links checked against the specified drawings, certification was awarded to the range for Back-up classification.

A witnessed report of performance was then required to prove full range capabilities of the fuse links. The full range tests were carried out as specified in IEC 282-1 (see section 2.2). A summary of the tests and results is shown in table 6.

Holec Test Laboratory					
Fuse Type	**Test Duty**	**LV Test Current**	**HV Test Current**	**Test Voltage (kV)**	**Remarks**
PP321a 40 A	3	56.9A (60 min) 65.4A (16 min)	40 A	12	OK
JP5-3R1					
Element 12 kV	3	56.7A (60 min) 64.3A (23 min)	40 A	12	OK

Table 6 Supplementary report of performance test results to prove full range capabilities of Fullran fuses using JP5-3R1 element design

5.6.2 Summary and Conclusions From Test Results

The new design for the 6.3 - 40 A DIN 'Fullran' fuse was fully tested to IEC 281-1 and now has a time / current characteristic which complies with the necessary transformer application standards.

In other words the major operation defect which prohibited the sale of the Fullran product into many European countries has been overcome.

Further details of the new operating characteristics are given in Chapter 8.

5.6.3 Analysis of the Tested Fuses

As with the fuses tested previously the fuses using the JP5-3R1 elements were opened up and analysed. The main interest was whether the introduction of 'arc-breaks' prevented the transfer of current between elements during the arcing process. Photographs of a fuse tested under TD2 conditions are shown in figures 34 and 35.

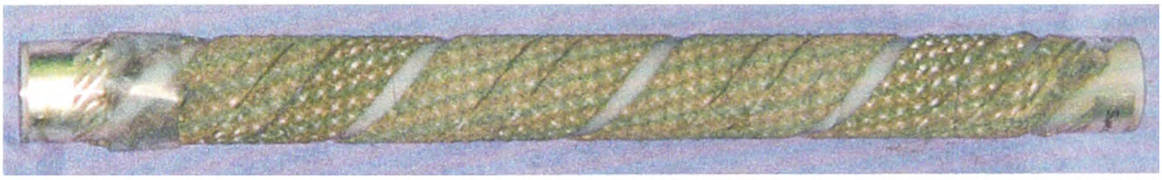


Figure 34 Fulgurite growth on JP5-3R1 element tested under TD2 conditions

Figure 35 Fulgurite growth on JP5-3R1 element tested under TD2 conditions

From the photographs it can be seen that that there is a definite improvement in the new design and that the introduction of arc breaks in the JP5-3R1 has improved the distribution of the fulgurite when compared with the original JP5-3 design. Unfortunately, in places the current has still been able to transfer over the larger gaps but the fulgurite distribution is more uniform. This indicates that it takes the current longer to cross these arc-breaks than to cross the conventional spacing. This must therefore be considered a definite improvement but not to the extent that was hoped for.

The movement of the bridges further away from the end collars in the JP5-3R1 design ensured that the arcing did not burn-back into the collar in the extent witnessed on the JP5-3 designs. Subsequently, this modification can also be considered an definite improvement.

5.6.4 Further Test Results With Fuses Using JP5-3 Element

Unexpected problems were encountered on this previously tested JP5-3 element type fuse. The fuse failed during the TD3 full range tests carried out at Holec Laboratories. In 50 % of the fuses tested, the porcelain barrel cracked during final clearance of the current.

Upon investigation of the tested fuse links it was found that there was a significant amount of burn back from the ends of the elements onto the collar, the contact spring and thus onto the caps. It was concluded that this excessive burn-back was the most likely cause of failure. A prevention to this mode of failure had already been introduced into the new JP5-3R1 design with the movement of the bridges further away from the collars (see sections 5.5.3 & 5.5.4).

Numerous tests were carried out to try and establish the cause of these failures either inherent design faults or production quality problems.

Element profile measurements were taken on the untested fuses from the same production batch. These were found to be within normal tolerances.

The sand compaction is a critical factor in fuse construction and insufficient compaction can cause excessive arcing, burn-back and fuse failure [29]. The function of the silica sand is to provide a labyrinth path of sufficient length through which the element metal is forced during the arcing period. It is important that the grain size of the sand is sufficiently coarse to provide gaps so that the volitalised metal is sufficiently dispersed to build up resistance quickly. At the same time the grain size must be small enough and the quantity sufficient to provide the necessary surface area for the cooling and deposition of the metal and to shield the barrel wall from the direct heat of the arc. Due to the granular form of the silica sand filling material, the sand must be compacted to ensure that the space between the core and the barrel remains fully occupied during subsequent movement whether by handling or by movement in operation [30].

Again fuses from the same batch were taken and the compaction level was tested. The results showed that the compaction was excellent and well within the prescribed production quality limits.

The only significant difference between the design tested in this series of tests to those previously tested was the introduction of the striker assembly. Once all the fuse elements have melted the current is transferred to the striker circuit and arcing continues along the striker coil, often the arc will transfer back to the main elements before final clearing, thus the introduction of the striker circuit can cause longer arcing times. In the case of the observed failures, it was concluded that the introduction of the striker caused longer arcing times resulting in the fulgurite burning back sufficiently to reach the end caps and body wall causing the fuse to fail.

As explained in section 5.3 having sufficient length of element, to build up dielectric strength during fuse operation, is a critical factor as the system voltage is increased. In order to determine the inherent safety margin in this 520 mm element design, a

TD1 shot was performed on one of the fuses with a voltage 13.8 kV and a test current of 52 kA. This voltage level is significantly higher than that necessary for a 12 kV rating and therefore would prove a good indication of safety margin.
The fuse cleared the fault effectively and upon further examination showed no signs of duress. This result gave further confidence in the decision to shorten the element length to accommodate 'arc breaks'.

5.7 Interim Conclusions

After extensive testing, a design was finalised for the 6.3 - 40 A range of Fullran fuse-links. The new design utilised a new concept in fuse element design - a multi-element bridge configuration which gave the necessary improvement in the time/current characteristics of the 6.3 - 40 A range of fuse-links.

The new design was fully tested to IEC 282-1 for full range fuse classification.

6. The Development of the 'Fullran' Full Range Fuse-Link 50 - 80 A Range

After the certification of the 6.3 - 40 A range, with improved characteristics, the next logical step was the development of the 50 - 80 A fuses to complete the range. It would be reasonable to expect similar improvements in characteristics by introducing the multi-element bridge design concept into the larger diameter fuse.

This chapter will illustrate the development work carried out on the remainder of the 12 kV Fullran fuse range, that is, the 50 - 80 A range.

6.1 Conventional 50 - 80 A Fullran Element Design

For rated currents of 50 - 80 A (12 kV), the fuse-element consists of a greater number of parallel strips attached to two concentric quartz tubes as shown in figure 36 (note, the inside of the quartz tubes have been 'blackened' for clarity). Again the fuse-link designs are identical apart from the thickness of the fuse-strips. The tube dimensions are 30 mm Dia.. x 320 mm length, with 15 element strips, and 43 mm Dia. x 281 mm length, with 20 element strips.

Figure 36 Finished 80 A Fullran fuse-link and the two quartz tube element assemblies that are in the design

The actual element strips mounted on the two different tubes are almost identical (the only difference being the number of strips and their helix angle). From figure 37, it can be seen that the elements consist of 15 or 20 notched elements connected in parallel. The alternate long / short notch pattern is used in these designs as used in the JP5-3R1 element pattern. The M-effect 'tin-spot' is situated at the centre of each strip (approximately 1 mm away from a notch - so that it is close to the area of highest current density, and hence highest temperature of the element).

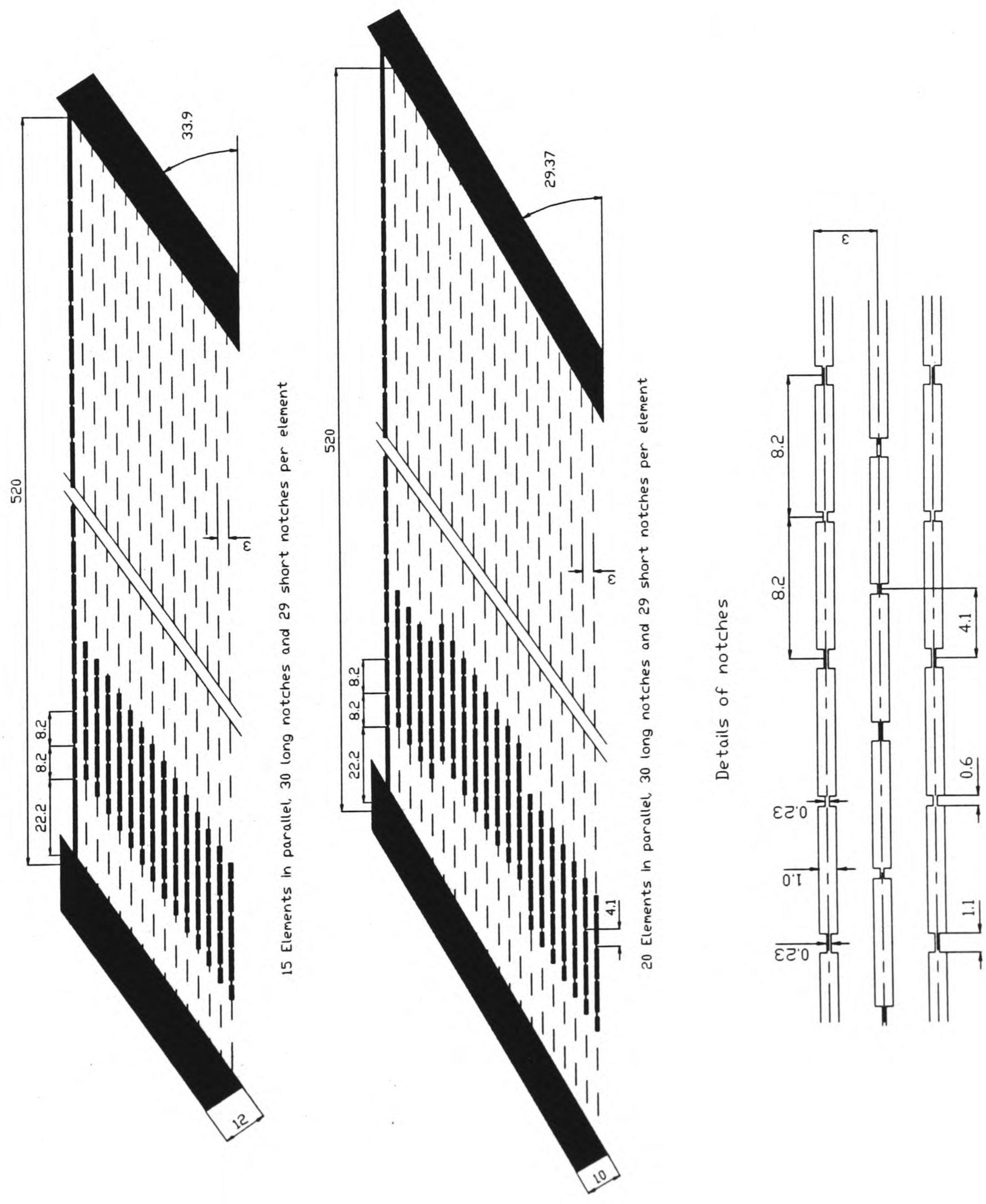


Figure 37 Element details of the Fullran 50 - 80 A range of fuse-links

6.2 Development of Double Tube Construction

There are no exact design criteria upon which fuse element design is based. The final design has to be a trade off of several conflicting design parameters. This section describes how the optimum design is evolved by considering each of these parameters in turn. The main parameters can be listed as follows:

- the number of elements
- the spacing between elements
- the length of the elements
- the number / pitch of notches
- the length of the notches
- the number and width of arc breaks

The easiest way to develop the design is to introduce the element design changes onto both the 30 mm & 43 mm tubes. Introducing different patterns onto the two tubes would mean it would be extremely difficult to predict the operation of the fuse with uneven current sharing and complex transfer of current during the arcing period.

All the design points learnt during the development of the 6.3 - 40 A range should be just as relevant in these designs, i.e. significant arc-breaks, the alternate length notches, the pitch and the location of the bridges with respect to the collar. The elements and element sets should be identical on the two different diameter quartz tubes as this ensures an even current distribution over all the elements.

Two different designs were produced in order to try and optimise the element patterns.

6.2.1 JP5-3B1 / JP7-3B1

The transfer of current was not completely eliminated with the introduction of two extra 1.5 mm breaks in the JP5-3R1 design. In order to put a stop to this transfer the arc-breaks need to be increased. One way of achieving extra spacing is to sacrifice element length. As explained in section 5.5, fuses are extremely voltage sensitive during the operating period. In order for the arc to be successfully suppressed the fuse must be able to build up enough dielectric strength so that the system voltage cannot maintain the arc. Dielectric strength is built up as the notches melt along the fuse elements due to this, the element length and the number of notches present is very critical [31]. A reduction in element length was considered a possibility due to the successful testing carried out on the 6.3 - 40 A range at higher than necessary voltages which indicated that the length of the element was greater than actually required for the 12kV rated voltage.

By reducing the element to 480 mm, from.the 500 mm used in the JP5-3R1 design, an extra 2 mm of spacing can be gained. Introducing this into the same location increased the arc-breaks to 4.5 mm either side of the middle element set. The element pattern was called the JP5-3B1 design and is shown in figure 38.

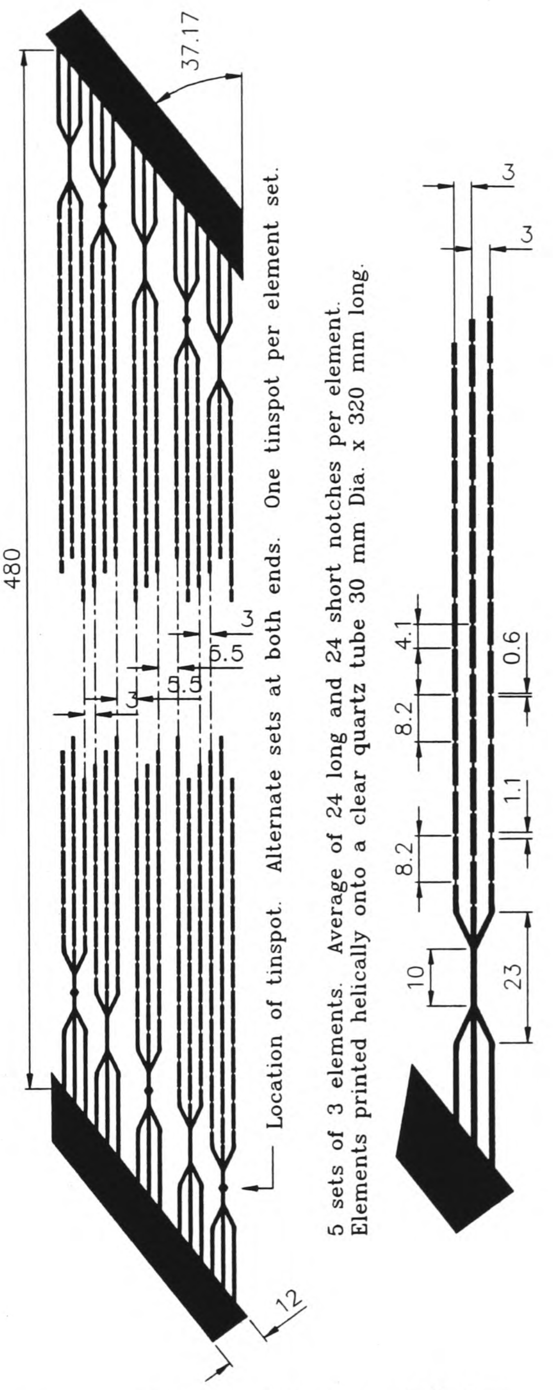


Figure 38 JP5-3B1 element design

The conventional Fullran design for the 43 mm tube had 20 element strips in parallel. In order to utilise the 3 element set bridge design, the number of elements has to be a factor of three. Therefore the number would have to be increased to 21 or decreased to 18. As previously stated, the element strips and element sets have to be identical in length and profile to those used on the 30 mm tube.

As more elements makes the TD3 shots easier, it was decided to go for the 21 element option. With a 21 element design, the total extra spacing for arc breaks was calculated to be 4 mm. It was decided therefore to have two arc-breaks of 4 mm (2 mm standard spacing + 2 mm extra). In order to retain symmetry in the design the arc-breaks were placed after the 2nd and 5th sets to give a 2-3-2 set combination called the JP7-3B1, as shown in figure 39.

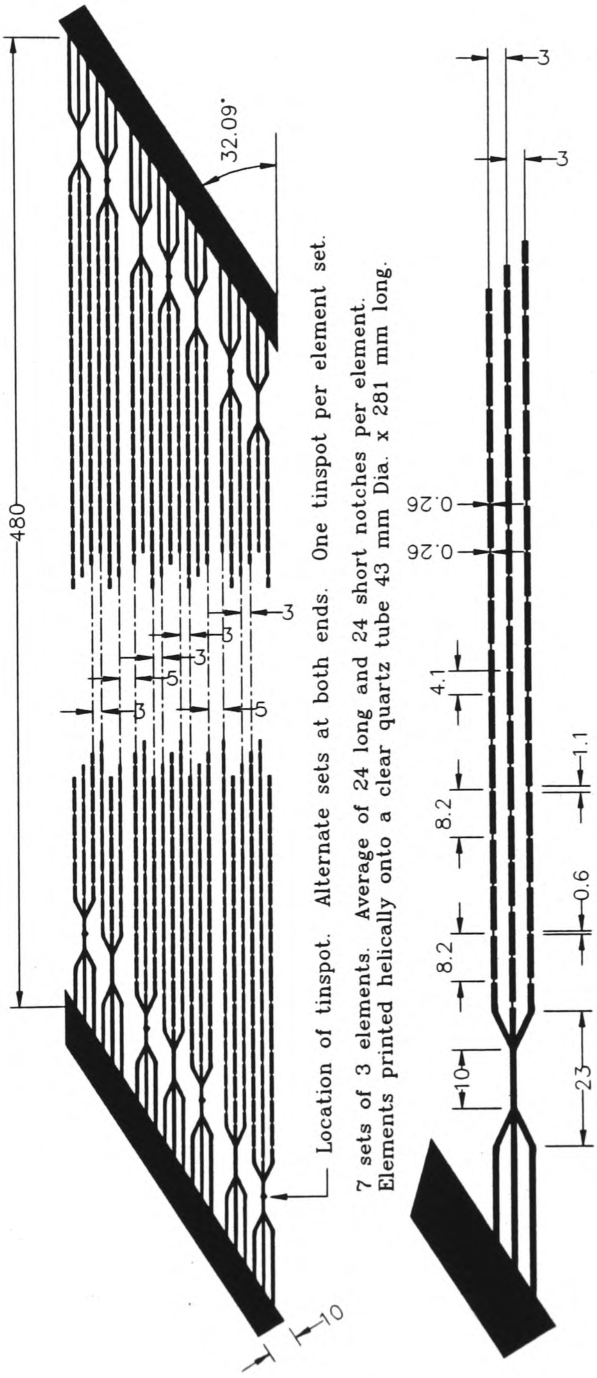


Figure 39 JP7-3B1 element design

6.2.2 JP5-3B2 / JP7-3B2

Another alternative design was produced with the criteria of keeping the same 500 mm element length but still achieving significant arc-breaks. One area which had not previously been investigated was the standard spacing between element strips. Looking at the element patterns, the reduction of the standard spacing between element strips from 2 mm down to 1.75 mm would give significant extra spacing for arc-breaks.

In the case of the 30 mm tube design the reduction in element spacing would result in an extra 6.5 mm spacing. It was decided to keep the 2-1-2 set formation as for the previous designs. The spacing between the first and last 2 element sets was increased to its normal 2 mm from the 1.75 mm between element strips within a set. The remaining 6 mm extra spacing was divided between the two arc-breaks to give the JP5-3B2 design as shown in figure 40.

In the case of the 43 mm tube the reduction in spacing between element strips resulted in an extra 6 mm available spacing (keeping a 21 element design). Again it was decided to keep the 2-3-2 set formation. The spacing between the sets without arc-breaks was again increased to the usual 2 mm. This resulted in an extra 5 mm spacing divided between the arc-breaks to give the JP7-3B2 design as shown in figure 41.

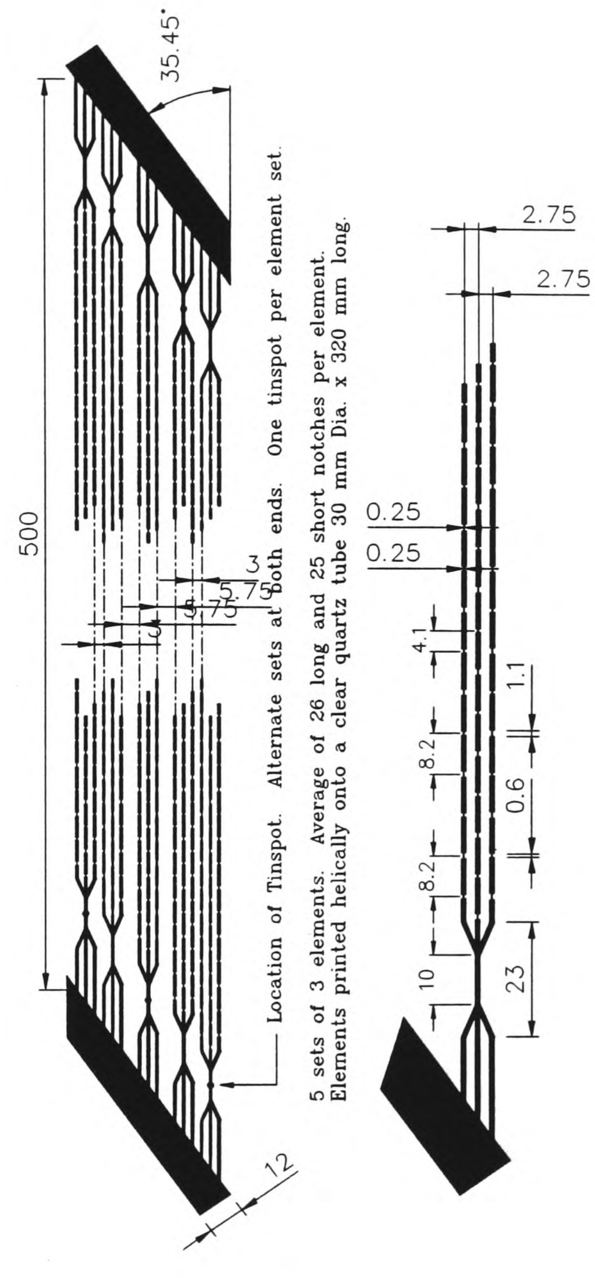


Figure 40 JP5-3B2 element design

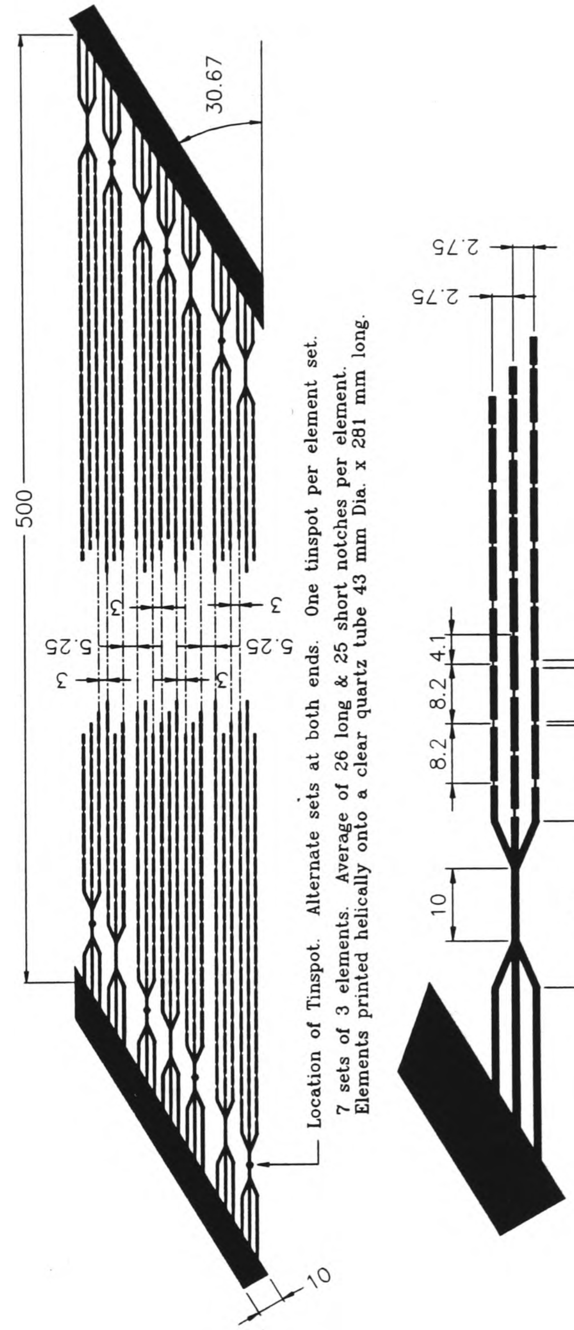


Figure 41 JP7-3B2 element design

6.3 Single Tube Construction

The double quartz tube construction is one approach to ensure full range performance. However, during the testing of the 6.3 - 40A range of fuses, two sample single 43mm tube designs were produced using an 18 element design based upon the same philosophy as the 40 Amp design, i.e. using a multi-element bridge with the fuse elements split into sets of three. The fuses were tested for full range performance at 63A. The results of the tests which were carried out at Holec's Laboratories are shown in table 7.

Fuse Type	Test Duty	Test Current	Test Voltage	Arcing Time	Remarks
JP6-3B1	3	63 A	12 kV	412 ms	OK
P321b 63A	3	63 A	12 kV	649 ms	OK

Table 7 Test Duty 3 development test results for single quartz tube construction 63A design

The results of the tests summarised in table 7 indicated that it may be possible to produce the 50 & 63 A ratings in a single 43 mm Dia. x 281 mm length quartz tube construction. This would be very desirable producing a 20% reduction in material costs and a significant reduction in production time.

The design of the element pattern for a single tube construction was further looked at after the original speculative tests. The element design finally chosen for the single tube fuses was the JP7-3B1 shown in figure 40. Whilst the 63 A fuse is considered very feasible, producing an 80 A fuse using this construction would be very unlikely. This is due to the thickness to which the elements would have to be plated resulting in a much lower current density being present in the notches upon initiation of arcing.

The element design chosen for the single tube fuses was the JP7-3B1 shown in figure 40. Whilst the 63 A fuse is considered very feasible, producing an 80 A fuse using this construction would be very unlikely. This is due to the thickness to which the elements would have to be plated resulting in a much lower current density being present in the notches upon initiation of arcing.

Whist an 80 A design in a single core construction would be outside the anticipated maximum current value, an attempt to produce one in a single tube construction was thought to be worthwhile as it would, at the very least, give an indication of the limitations of the design.

6.4 Testing of the Designs

As no previous problems had been experienced with TD1 & TD2 tests (for the 6.3 - 40 A range), it was decided to begin the testing process with the TD3 full range performance tests at the Holec Laboratories.

Holec Test Laboratory				
Fuse Type	**Test Duty**	**HV Test Current**	**Test Voltage (kV)**	**Remarks**
12 kV, PP321a, 80 A	3	80 A	12	OK
JP5-3B1 & JP7-3B1 Elements	3	80 A	12	OK
12 kV, PP321a, 80 A	3	80 A	12	OK
JP5-3B2 & JP7-3B2 Elements	3	80 A	12	OK
12 kV, PP321a, 80 A JP7-3B1 Element	3	80 A	12	Fuse Exploded
12 kV, PP321a, 63 A	3	63 A	12	OK
JP7-3B1 Element	3	63 A	12	OK

Table 8 Test Duty 3 test results for developed 80 & 63 A Fullran fuses

As expected the 80 A single tube construction failed to pass the full range performance test. All the other designs passed the TD3 full range test without any problems, these being double cored.

The next stage in the process was to test the new designs to for Test Duties 1 & 2 performance. The testing was carried out at the KEMA test station.

KEMA Test Station IV				
Fuse Type	**Test Duty**	**Test Current (kA)**	**Test Voltage (kV)**	**Remarks**
12 kV, PP321a,	1	40.6	10.80	OK
80 A	1	40.6	10.80	Fuse Exploded
JP5-3B1 & JP7-3B1 Elements	1	25	10.50	Fuse cleared but porcelain cracked after a few seconds.
	1	25	10.5	Fuse cleared - only just
12 kV, PP321a,	1	40.6	10.8	Fuse Exploded
80 A. JP5-3B2	1	25	10.5	Fuse Cleared
JP7-3B2 &	1	25	10.5	Fuse Exploded
Elements				
12 kV, PP321a,	1	45	12.0	Fuse Cleared
63 A	1	45	12.0	Fuse Exploded
JP7-3B1	1	40.6	10.8	Fuse Cleared
Element	1	40.6	10.8	Fuse Exploded

Table 9 Test Duty 1 test results for developed 80 & 63 A Fullran fuses

As shown in table 9, all the fuses experienced unexpected problems with the Test Duty 1 tests. The results from table 9 show that the first design tested, the 80A fuse designed with JP5-3B1 and JP7-3B1 elements, had a variable performance under TD1 conditions. The first test carried out with a current of 40.6kA was passed successfully. However, the repeat test exploded. After reducing the current to 25kA, the next fuse also failed to clear successfully. These results indicate that the fuse tested first would more than likely be on the borderline of failure. The reason why one fuse can pass at 40.6kA and the next fail at 25kA can be explained by the fact that due to the current-limiting effects of fuses, i.e. the fuses ability to cut off the current before the peak value is approached, the difference in the stress that a fuse is under when clearing a 40kA or 25kA prospective fault current is minimal.

In summary, the fuses that did pass the test did so in an uncontrolled manner and over 50 % of those tested exploded.

6.4.1 Analysis of Tested Fuses

The fuses that passed the test were opened and examined in order to try and determine the cause of failure.

Figure 42 shows a photograph of a typical example of a fuse that had passed but had been extremely close to failing. Figure 43 shows a photograph of all that was left of one of the failed fuses.

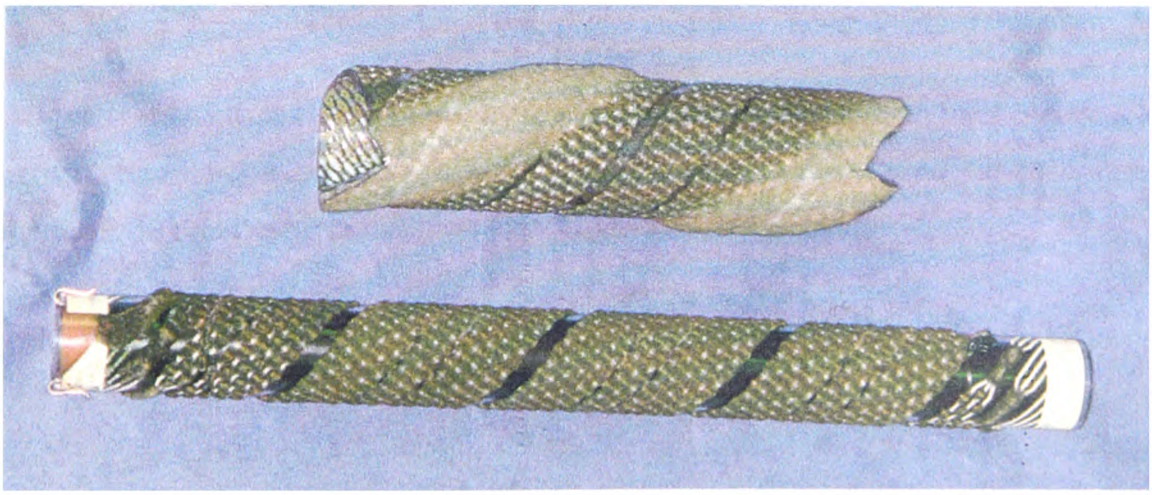


Figure 42 Photograph of 80 A fuse JP5-3B1 & JP7-3B1 elements after TD1 shot (fuse just passed test)

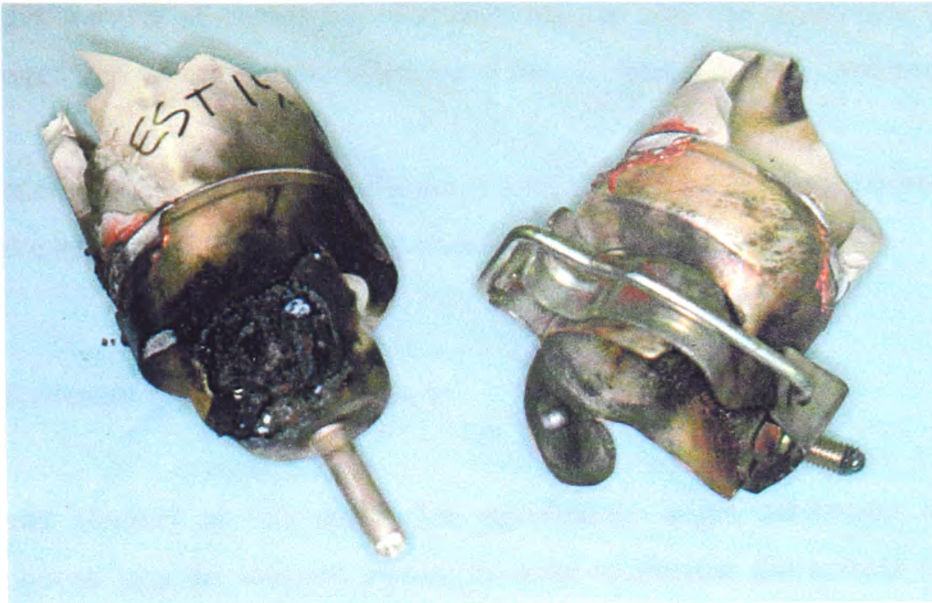


Figure 43 Photograph of the remains of an 80 A fuse after a TD1 failure

It can be seen from figure 42, that there were no problems observed on the 30 mm quartz tube which indicates that the spacing between the elements was sufficient to prevent any current transfer. This was certainly not the case with the 43 mm tube. It can be seen that the current has transferred across the elements, breaching both the arc-breaks and even the standard printing gap. This transfer of current effectively greatly reduces the length of the element causing a massive fulgurite growth. The fulgurite will grow to such an extent that it will reach and shatter the porcelain barrel during operation causing the fuse to explode.

All the fuses analysed showed the same effect taking place - in both the 80 A double construction designs and the single construction 63 A design. In all the 80 A fuses the inner 30 mm quartz tube showed no signs of any stress at all.

6.4.2 Conclusions from the Tests

Unexpectedly, the problem tests for the fuses was no longer the TD3 full range tests but the short circuit breaking tests.

It was concluded that the problems experienced by the fuses can be attributed to a massive transfer of current between elements and over the arc-breaks, this causing a massive build up of fulgurite which burst the fuse barrel causing catastrophic failure.

In order to overcome these problems at least the 43 mm element required redesigning to take into account this potential transfer of current.

6.5 Redesign of the Fuse Elements

It was obvious at this stage that significantly larger arc-breaks needed to be introduced into the element pattern in order to prevent the current transfer. This would be impossible to achieve whilst keeping a 21 element strip pattern. Therefore the first decision was to reduce the number of element strips from 21 to 18.

The next stage was to decide what length of element was required. The shorter the element length the bigger the fulgurite growth when the fuse is operating (due to the arcing being concentrated over a smaller length causing it to continue longer in any particular location) hence, current transfer will be more likely. Therefore it was decided to keep the element length at a minimum value of 500 mm (as used in the 6.3 - 40 A range).

The element designs JP5-3B2 and JP7-3B2 had a reduced spacing between element strips within the element sets. Obviously the closer the strip are together the easier it is for the current to transfer from one to the other. Therefore it was decided to abandon the idea of reducing the spacing between element strips.

6.5.1 JP6-3B2 Element

With all these points decided it was just a matter of arranging the formation of the element sets in the best possible manner. As discussed previously, the element strips and sets for the 43 mm tube must be identical for those of the 30 mm tube. One element design that met the required criteria for the 30 mm tube was the JP5-3R1 element. Using this design for the 30 mm tube significantly reduced the redesign work necessary for the 80 A double tube construction fuses.

The new 43 mm tube element design therefore used the element strips and sets used in the JP5-3R1 design. Using these elements and reducing the number of sets down from 7 to 6 enabled an extra 10 mm of spacing to be introduced for arc-breaks. It was shown from the test results of the previous design, that the arc-breaks really needed to be of a significant width to prevent transfer of current. Bearing this in mind, a 2-2-2 set configuration with 2 x 7 mm arc-breaks was designed as shown in figure 44.

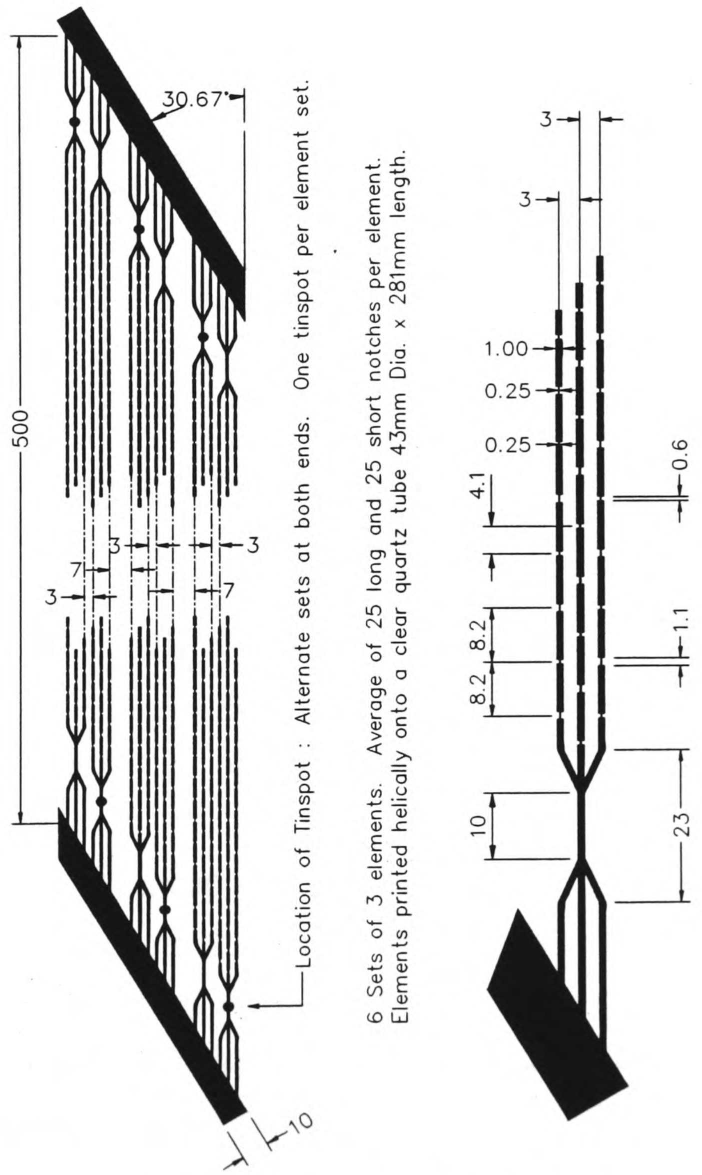


Figure 44 JP6-3B2 element design

6.5.2 Double Tube Construction for 80 A Fuses

One double tube construction was developed using the JP6-3B2 & JP5-3R1 element designs as described. The main difference in this 80 A design was the reduction in the number of elements by three to accommodate the arc-breaks.

6.5.3 Single Tube Construction for 50 & 63 A Fuses

The 63 A single tube design replaced the old JP7-3B1 element pattern with the new JP6-3B2 pattern. This would make the TD3 full range tests more difficult but it was felt that there was enough in hand in the designs to carry on with this single tube design.

6.6 Type Testing of the 50 - 80 A Fuses to IEC 282-1

6.6.1 Type Test Results

After the difficulties experienced with TD1 on the previous designs, the TD1 & TD2 performance was tested first. This time the tests were carried out at the Falcon Testing Laboratories in Loughborough, Leicestershire.

Table 10 provides a summary of the test results showing how the new 80 A and 63 A designs passed the TD1 & TD2 requirements for certification to IEC 282-1.

The current used in TD1 was 20 kA rather than the 40 kA previously tested as this current was the maximum current capability of the Falcon Test Station at 12kV. The IEC 282-1 standard allows test duties 1 and 2 to be carried out at 87 % of rated voltage +5% -0% (approximately 10.4kV for a 12kV rated fuse). The fuses were tested at a higher than necessary voltage level (the more critical factor), 12kV and 12.6kV for the 80 A and 63 A designs respectively. The test voltages being 15 % and

20 % higher than necessary provides assurance that there is a certain amount of safety margin in the designs and that the fuses should have no trouble clearing short circuit faults at the correct voltage level.

Falcon Testing Laboratory				
Fuse Type	**Test Duty**	**Test Current (kA)**	**Test Voltage (kV)**	**Remarks**
12 kV, PP321a, 80 A JP5-3R1 & JP6-3B2 Elements	1	20.0	12.0	OK
	1	20.0	12.0	OK
	1	20.0	12.0	OK
	2	4.8	12.0	OK
	2	4.8	12.0	OK
	2	4.8	12.0	OK
12 kV, PP321a, 63 A JP6-3B2 Element	1	20.4	12.6	OK
	1	20.4	12.6	OK
	1	20.4	12.6	OK
	2	2.8	12.6	OK
	2	2.8	12.6	OK
	2	2.8	12.6	OK

Table 10 Test Duty 1 & 2 results for modified 63 & 80 A designs

The Test Duty 3 Full Range shots were then performed, once again at the Holec Testing Laboratories. The results are shown in table 11.

Holec Test Laboratory					
Fuse Type	**Test Duty**	**LV Test Current**	**HV Test Current**	**Test Voltage (kV)**	**Remarks**
12 kV, PP321a, 80 A	3	113A (60 min) 131A (29 min)	80 A	12	OK
JP5-3R1 & JP6-3B2 Elements	3	113A (60 min) 131A (38 min)	80 A	12	OK
12 kV, PP321a, 63 A	3	90A (60 min) 103A (10 min)	63 A	12	OK
JP6-3B2 Element	3	90A (60 min) 103A (2 min)	63 A	12	OK

Table 11 Test Duty 3 (full range) results for modified 63 & 80 A designs

Analysing all the results, the two designs passed all the type tests necessary for certification to the IEC 282-1 standard.

6.6.2 Analysis of the Tested Fuses

The tested fuses were opened and inspected in order to determine whether the design changes had worked in the expected manner and also to determine whether the fuses were at all near failing. Figure 45 shows a photograph of an 80 A design after testing to TD1.

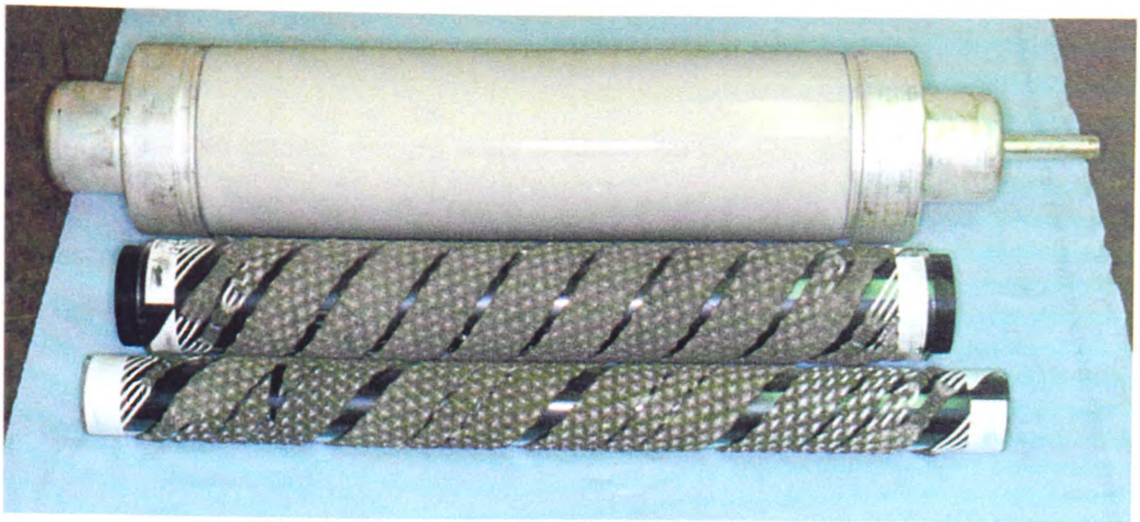


Figure 45 Photograph of an 80 A design after testing to TD1 (JP6-3B2 & JP5-3R1 elements)

It can clearly been seen from the photograph that the current distribution is very even over the two quartz tubes. The arc-breaks introduced in the 43 mm JP6-3B2 design have not been breached at all. The 30 mm tube has then same type of distribution as the 40 A fuses which use the same element design.

All the tested fuses were opened and the same results were observed in each case.

6.6.3 Summary and Conclusions From Test Results

The undesirable operating characteristics of the original Fullran fuse-links in the region of the 1 second operating time which were highlighted in section 2.6 and shown in figure 8, had been the major operational defect which prohibited the sale of the Fullran product into many European countries.

The new design for the 50 - 80 A DIN 'Fullran' fuse was fully type tested to IEC 282-1 and the time / current characteristic now complies with necessary transformer application standards therefore, these problems have been overcome.

Further details of the new operating characteristics are given in Chapter 8.

6.7 Interim Conclusions

After extensive testing, designs were finalised for the 50 - 80 A range of Fullran fuse-links, thereby completing the entire 12 kV Fullran range. The new designs again utilised a multi-element bridge configuration which gave the necessary improvement in the time/current characteristics of the 50 - 80 A range of fuse-links.

The new designs were fully tested to IEC 282-1 for full range fuse classification.

7. Mathematical Modelling of Pre-arcing Fuse Operation

As outlined in chapter 1, one of the specific overall objectives of the Teaching Company programme was 'to fully investigate the operating characteristics of the 'Fullran' fuse design using mathematical modelling and other simulation techniques'.

Mathematical modelling of fuse operation has been attempted by various means for over 25 years. The most common numerical methods have been based on finite difference and finite element techniques [23, 32, 33]. Most of these models have concentrated on the area of operation prior to the M-effect taking place.

Another method of modelling is based upon the theory of using electrical analogues. This has been used to simulate long-time operation taking M-effect diffusion into account. The method was based on modelling both temperature and diffusion as electrical analogues and utilising a computer circuit analysis software package to simulate the resulting circuitry [16, 34]. The use of electrical analogues was also used to simulated the heat flow in a Fullran high voltage fuse, the analysis being performed interactively on the screen of a personal computer [35].

Mathematical modelling of fuse operation has always proved to be very difficult to achieve to a great accuracy i.e. within 10%. However, the huge advances in personal computer power and the emergence of user friendly Finite Element Analysis computer packages has made this numerical method much easier to utilise. Due to these enhancements it was decided to concentrate the effort in this particular field of mathematical modelling.

7.1 Finite Element Analysis

Virtually every phenomenon in nature can be described, with the aid of the laws of physics, in terms of algebraic, differential, or integral equations relating various quantities of interest. Generally, the derivation of the governing equations for most problems is not unduly difficult. However, their solution by exact methods of analysis is a formidable task.

Finite element analysis works by first of all representing a geometrically complex domain as a collection of geometrically simple sub-domains, called finite elements. Secondly, over each finite element, approximation functions are systematically derived using the basic idea that any continuous function can be represented by a linear combination of algebraic polynomials. Finally, the equations over all elements of the collection are connected by the continuity of the primary variable or variables, the boundary conditions of the problem are imposed, and then the connected set of equations is solved.

There are a number of finite element analysis computer packages available. One of the leaders in the field is the widely used ANSYS package produced by Swanson Analysis Systems Inc. This package is particularly suitable for modelling of fuse operation as it has the ability to analyse coupled-fields, that is, one that takes into account the interaction (coupling) between two or more disciplines of engineering.

A fuse element can simply be described as a current-carrying conductor with a temperature- dependent resistivity. The coupling effects in this case are recursive, that is, the flow of current raises the temperature of the element. The rise in temperature changes the element's resistivity, which changes the value of the current, which in turn changes the temperature distribution, and so on.

The coupled-field in this case is therefore 'Thermal-Electric' which is used to determine the temperature distribution in a conductor due to joule heating effects from the flow of electric current.

7.2 Modelling of the Fullran Fuse

The mathematical model was to be initially developed to simulate the conventional Fullran design, the plan being to eventually expand the modelling and the development process concurrently. This work is ongoing.

The work which has been carried out to date on modelling does provide an indication into the operation of the Fullran fuses with respect to heat losses and also offers a good platform from which the model can be significantly developed.

The modelling procedure in ANSYS can be simply divided into six basic steps:

1. Define material properties involved in the model
2. Define the geometry of the model
3. Produce the finite element mesh
4. Apply the loads and set boundary conditions (current, temperature, voltage etc.)
5. Solve the analysis
6. Display and analyse the results

7.2.1 Definition of Material Properties

Initially the developed model will only be concerned with the silver strip and the quartz tube upon which it sits. The material properties of silver and fused silica (quartz tube) are listed together with the labels used by ANSYS.

Silver

thermal conductivity (Kxx)	429 W m^{-1} K^{-1}
density (DENS)	10500 kg m^{-3}
specific heat (C)	235 J kg^{-1} K^{-1}
constant for silver α	0.0045 K^{-1}
resistivity ρ (rsvx)	$\rho = \rho o\ (1 + \alpha\ (T - To))$
ρo (T = 295K)	1.63 e^{-8} Ωm

where ρ = resistivity at temperature T

ρo = initial resistivity

α = constant relating to material

T = temperature

To = initial temperature

Fused Silica (SiO_2) - Quartz tube

thermal conductivity (Kxx)	1.33 W m^{-1} K^{-1} at 273.2 K
	1.48 W m^{-1} K^{-1} at 373.2 K
	2.4 W m^{-1} K^{-1} at 873.2 K
density (DENS)	2.2 kg m^{-3}
resistivity ρ (rsvx)	1 e^{+16} Ωm

The resistivity value for silver shown above is that for a pure silver strip. There is however, an anomaly that must be taken into account when dealing with the Fullran type fuse.

The resistance of a fuse-link consisting of silver strip can be roughly calculated using the following formula:

$$R = \frac{\rho}{N.t}\left\{\frac{Lstrip}{Wstrip} + \frac{Lnotch}{Wnotch}\right\} \cdots (1)$$

Where R = fuse resistance

ρ	= resistivity of silver
N	= number of fuse strips
t	= thickness of fuse strips
Lstrip	= total length of main fuse strip
Wstrip	= width of main fuse strip
Lnotch	= combined length of all notches
Wnotch	= width of notches

Now when the conventional 40 A Fullran design was developed, the final fuse parameters were as follows:

$R_{practical}$	= 22.5 mΩ
N	= 15
t	= 38 μm
Lstrip	= 482.2 mm
Wstrip	= 1.05 mm
Lnotch	= 37.8 mm
Wnotch	= 0.31 mm

Substituting these values in equation (1) above, we come up with a theoretical resistance of :

$$R_{theoretical} = 16.6 \text{ m}\Omega$$

There is obviously a significant discrepancy between this theoretically derived figure (based on pure silver) and the practically achieved figure.

Part of the difference can be explained by the formula used for calculating the resistance. Basically the formula calculates the theoretical resistance values of all the band and notch sections of fuse element and then adds them together as a series resistance. However, when current flows in a notched section of element, the corners of the band sections do not carry any current due to the pattern of the current flow.

As the formula considers the current to be shared by all parts of the element, there will be a certain difference in the theoretical and calculated resistance values.

However, the level of disagreement in the theoretical and calculated values would indicate that the crudeness of the formula is not the sole reason for the discrepancy in values.

A sample of silver printing paste used in the manufacture of Fullran fuses was analysed in order to try and further explain the difference between the theoretical and practical resistance values.

7.2.1.1 Analysis of Silver Paste

After silver paste has been deposited onto the quartz tube, via. screen printing, it is cured in an oven at an elevated temperature. The curing has the effect of 'activating' the bonding mechanisms in the paste and also driving off any remaining impurities. The silver paste layer must be chemically bonded to the quartz in some way so that the silver does not peel off as the thickness of plating is increased. Putting it simply, the bonding method used in silver paste used on the Fullran fuse involves the paste very slightly etching into the surface of the quartz with the etch being taken up by 'fluxes' from the paste to which the silver is attached.

The results of an electron microscope scan carried out on the silver of a Fullran 40 A fuse are shown in figure 46. It can be seen from this that the deposit is very close to pure silver but with a small amount of impurity deriving from the 'flux' layer of the silver paste deposit. These impurities will obviously have an effect on the practical resistivity of the silver strip (with a diminishing effect as the percentage of impurity in the strip decreases with increasing silver deposit).

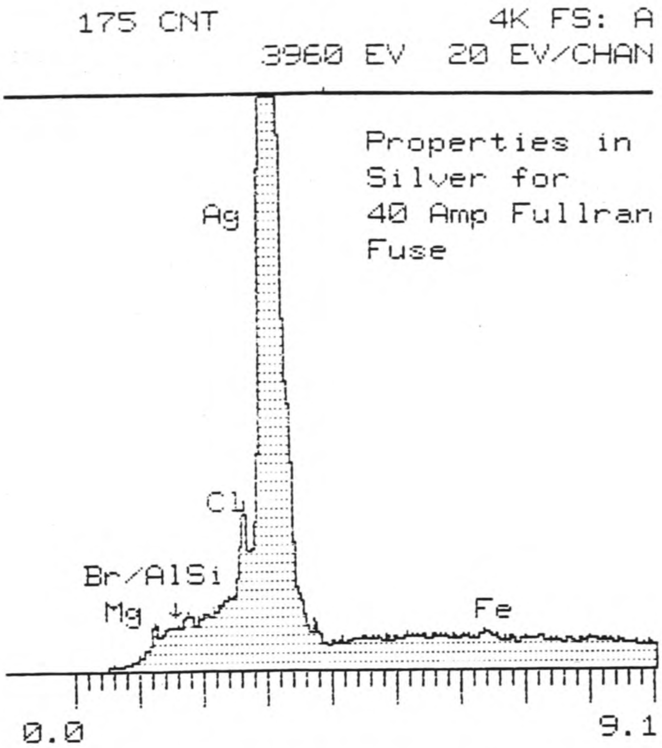


Figure 46 Electron microscope scan of Fullran 40 A silver strip

Another study simply involved placing a section of quartz tube with a deposit of silver paste (prior to silver plating) under high magnification. The results are shown in figures 47 and 48.

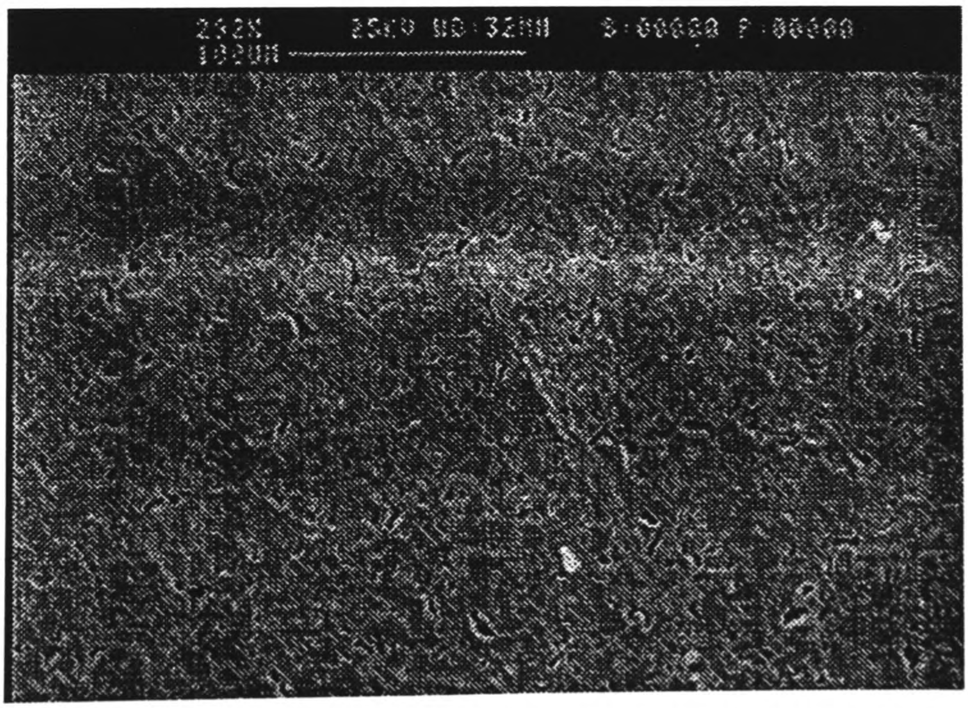


Figure 47 3x magnification of silver strip prior to silver plating

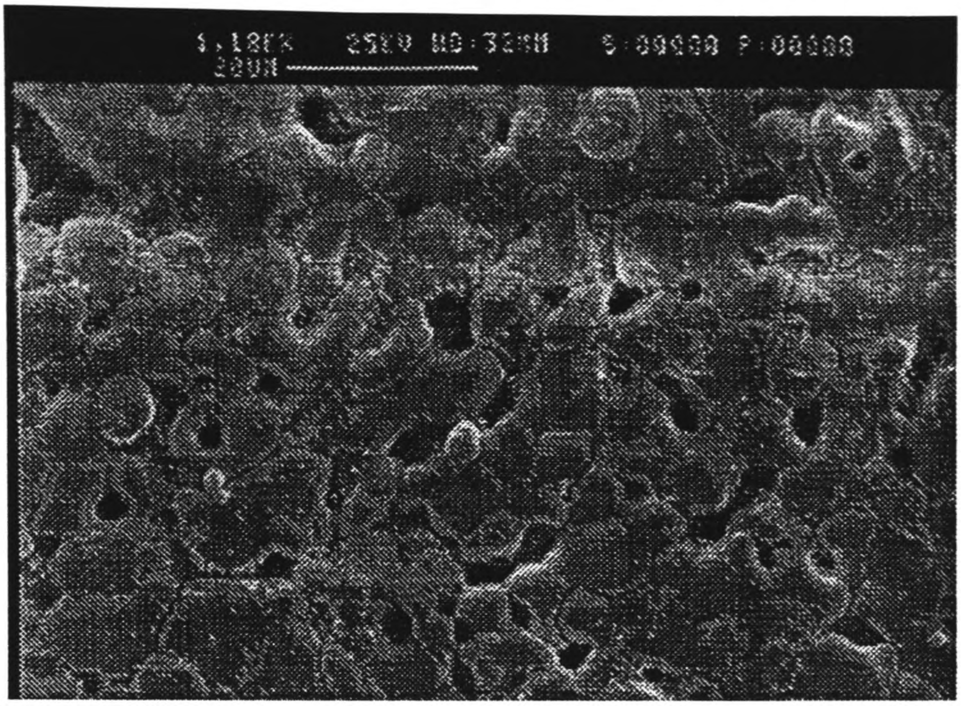


Figure 48 12x magnification of silver strip prior to silver plating

The results show that the deposit is not completely uniform with a number of small holes present in the strip. These gaps are completely covered up when silver is deposited onto the strip during silver plating. However, the practical resistance of the strip would be effected - again with a diminishing effect as the silver deposit increased.

The combination of these two factors together with the basic formula used to calculate the theoretical resistance could therefore explain the discrepancy in the theoretical and practical resistance values of the fuses.

7.2.1.2 Modification of Silver Resistivity for Modelling Purposes

This conflict in the practical and theoretical values of resistance had to be taken into account in the mathematical modelling. To accommodate the difference it was decided to obtain an 'effective resistivity' value for the Fullran 40 A silver strip and suitably modify the silver material properties. This was done by rearranging equation (1) to give :

$$\rho = \frac{R.N.t}{\left\{\frac{Lstrip}{Wstrip} + \frac{Lnotch}{Wnotch}\right\}} \ldots(2)$$

substituting in the known practical values we obtain,

$$\rho_{effective} = 2.21\ \mathrm{e}^{-8}\ \Omega\mathrm{m}$$

Therefore this resistivity value was substituted into the silver material properties for the mathematical modelling.

7.2.2 Geometry of the Model

In order to establish the viability of using the ANSYS package for mathematical modelling of fuse performance, it was decided to begin using a simple 2-dimensional model of the silver strip and surface of the quartz tube only. (A 2-D model can be employed with the correct selection of element type and a suitable modification to the material properties, see 7.2.3.1).

As stated previously, the modelling will concentrated on the area of operation where arcing is initiated at the notches. By symmetry, only a small section consisting of half of a notch and half of a band needs to be considered in the simply model. Similarly as the initial modelling will only consider the surface of the quartz tube upon which the silver elements sit (ignoring the surrounding silica sand and the thickness of the quartz), only half of the width of clear quartz between elements needs to be taken into consideration in the model. The actual geometry of the model is shown in figure 49.

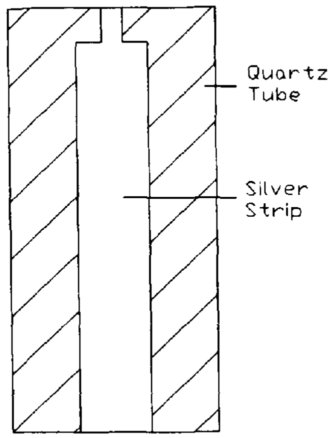


Figure 49 Geometry of the simple model used in ANSYS simulation

Once the model has been defined in the programme and the correct materials are assigned to the relevant areas, the model must be meshed.

7.2.3 Production of the Finite Element Mesh

To carry out a thermal-electric analysis in ANSYS, one of the following element types must be used:

LINK68	the coupled thermal-electric line
PLANE67	the coupled thermal-electric quadrilateral
SOLID69	the coupled thermal-electric brick

The most convenient element type to use for the initial model was the PLANE67 element type.

7.2.3.1 Features of the PLANE67 Coupled Thermal - Electric Element [36]

Each node has two degrees of freedom - Voltage and Temperature.

It is a 2-D solid element with thermal and electrical conduction capability. Joule heat generated by current flow is also included in the heat balance.

The element is applicable to a two-dimensional (plane or axisymmetric), steady-state or transient analysis.

Both electrical resistivity (rsvx) and thermal conductivity (Kxx) must be defined. They may be constant or temperature dependent.

The PLANE67 element assumes a unit thickness; it does *not* allow thickness input. If the actual thickness (t) is not unity, the material properties need to be adjusted as follows: *multiply* the thermal conductivity and density by t, and *divide* the electrical resistivity by t.

No electrical capacitance or inductance effects are included.

It requires an iterative solution for thermal-electric coupling.

Applicable loads are Temperature, Voltage, Current, Heat Flow Rate, Heat Generation Rate, Convection and Heat Flux.

Restrictions and assumptions that apply for PLANE67 are:

- The element must lie in an X-Y plane.
- Free surfaces are considered to be adiabatic.
- Current flow and heat flow must be in the same plane.
- If a current is specified at the same node that a voltage is specified, the current is ignored.
- The specific heat and enthalpy are evaluated at each integration point to allow for abrupt changes (such as for melting) within a coarse grid.

- The Joule heat generated in a substep is used in the temperature distribution calculated for the next substep.

Once the element type had been chosen, the next step was to decide on an appropriate mesh density.

7.2.3.2 Mesh Density

Mesh density is an extremely important parameter in finite element analysis. If the mesh is too coarse, results can be seriously in error; if the mesh is too fine, it will lead to a waste of computer resources, excessively long run times will be experienced, and there will be a distinct possibility that the model could be too large for the average computer system.

Unfortunately, there is no definitive answer to the question of "How fine should the element mesh be in order to obtain reasonably good results?". One method of coming up with an acceptable mesh density can be described as follows:

Perform an initial analysis using a "reasonable" mesh. The problem should then be reanalysed using twice as many elements in critical regions, and the results compared. If the two meshes give nearly the same results, then the mesh is probably adequate. If the two meshes yield substantially different results, then further mesh refinement might be required. The mesh should be redefined until identical results are obtained for succeeding meshes.

This technique was used on the model geometry shown in figure 49. The critical area of the model is in the notch and therefore the mesh density was concentrated in this region. An element plot of the model is shown in figure 50.

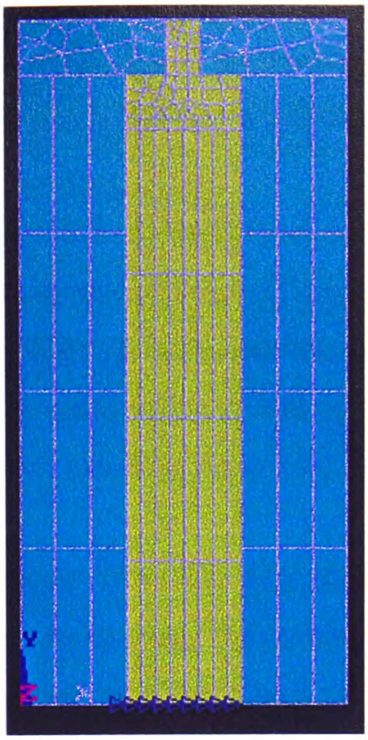


Figure 50 Element plot of model

Once the model has been generated and meshed, loads can be applied and solutions obtained.

7.2.4 Loading and Solution

The primary objective of a finite element analysis is to examine the response of a structure or component to certain loading conditions. Specifying the proper loading conditions is, therefore, a key step in an analysis.

"Loads" include boundary conditions as well as externally or internally applied forcing functions. In the thermal-electric case, examples of loads are : temperatures, heat flow rates, convections, internal heat generation, electric potentials and electric current.

With the use of load step options in the ANSYS program, how loads are actually used and applied during solution can be controlled. A load step is simply a configuration of loads for which a solution is obtained.

The modelling carried out in this case only used two load steps. Load step 1 was a steady-state load step in which boundary conditions were defined in order to establish the initial conditions of the fuse. The second load step was a transient load step and applied the fault current, via a step increase, and spanned a relevant amount of time in order to encompass the notch reaching the melting point of silver.

For this model, the assumption was made that pre-arcing time of the fuse was equal to the time taken for the notch to reach the melting point of silver (1234 K). Whilst this assumption neglected the time for which silver is in a molten state for the purposes of model verification, it has previously been shown that for accurate calculation of short-circuit pre-arcing operations, the time an element is in a molten state does need to be taken into account [37].

The fault current was applied to the model by coupling together all the nodes along the bottom edge of the model and applying the force (defined as electric current in amperes). In order to allow the current to flow, the nodes along the top edge of the model were coupled together and a tied to a Voltage zero.

Appendix B shows the listing of an example 'log file' (which lists all commands input into ANSYS) complete with comments explaining the functions of the commands.

Once the solutions to all load steps have been obtained, the results of the analysis can be reviewed by post-processing.

7.2.5 Post-processing

Post-processing is the most important step in the analysis as it is where the mesh parameters are evaluated to determine how the applied loads affect the design, how good the finite element mesh is, and so on.

ANSYS has two available post-processors, one general and one time-history. The general post-processor (POST1) allows the results to be reviewed over the entire model at specific load steps or at specific time points. For this model, the processor enabled contour plots of temperature to be obtained, see figure 52.

The time-history post-processor (POST26) enables variation in particular result items at specific points in the model to be reviewed with respect to time. In this case it allowed the temperature at particular nodes to be plotted against time, see figure 53.

All the results of the analysis are written to results files which can then be reviewed at leisure.

7.3 Results Obtained From Model

The initial model was developed, as described in section 7.2, with the purpose of establishing the viability of using the ANSYS package for mathematical modelling of fuse performance. Initially the model was to attempt to simulate the pre-arcing behaviour of a conventional Fullran fuse prior to M-effect operation.

The model was loaded with prospective fault currents which have melting times in the region of 1×10^{-6} up to 0.1 seconds. The results of the simulation are shown in table 12 and also plotted on a time/current curve in figure 51.

Ip	Conventional Fullran tv (s)	Model Time to Reach 1234 K (s)
44 kA	1×10^{-6}	5.3×10^{-7}
4.4 kA	1×10^{-4}	5.5×10^{-5}
1.37 kA	1×10^{-3}	7.9×10^{-4}
900 A	3×10^{-3}	2.9×10^{-3}
564 A	1×10^{-2}	1.6×10^{-2}
456 A	3×10^{-2}	3.2×10^{-2}
425 A	1×10^{-1}	3.7×10^{-2}

Table 12 Mathematical model results

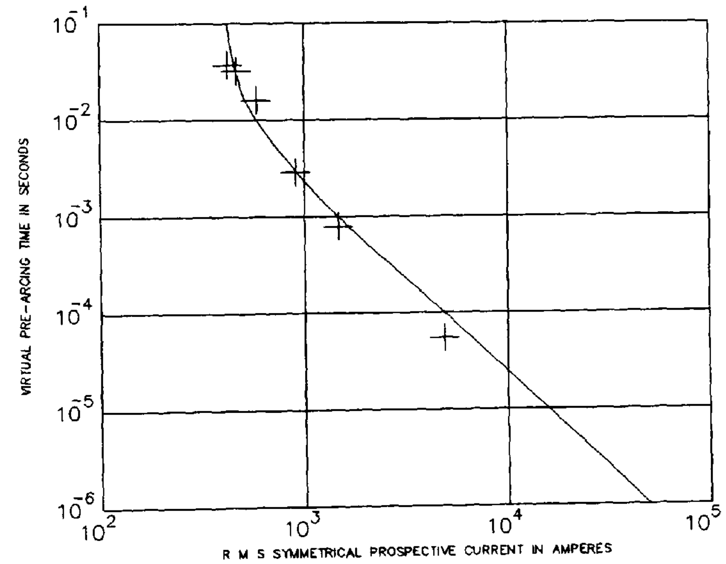


Figure 51 Model results plotted against conventional Fullran curve

It can be seen from these results that the model gives a fair representation of the time/current curve at least up to the 3×10^{-2} second region. For the fastest time simulated, the accuracy is -30% on current but for all other values up to 3×10^{-2} seconds the accuracy is ±12% on current.

7.3.1 Analysis of Results

The easiest region of operation to simulate is the adiabatic region of operation, that is the area where there are no heat losses involved (i.e. all the energy input to the fuse is used to melt the silver strip). Generally the region with melting time $\leq 1\text{x}10^{-4}$ seconds is considered to be adiabatic [8].

The results obtained from the model for the times in this region show that there is very little heat lost from the notch to the main strip (or the surrounding medium) during this period. The figures show that the melting time for the notch has increased almost exactly by a factor of 100 as the fault current has decreased by a factor of 10, which indicates adiabatic operation.

The temperature profile plot shown in figure 52 shows that virtually all the heat built up due to the current flow is maintained in the notch. Note that the plot shows only the silver part of the model for clarity. It can be seen that there is very little difference in the temperature of the main strip over its entire length (310 K at centre of strip) and a big difference between the temperatures at the notch (1234 K at centre of notch) and on the strip.

Figure 53 shows a plot of the temperature increase of a node at the centre of the notch verses time.

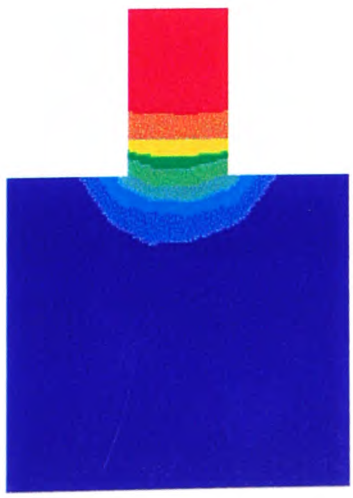


Figure 52 Temperature profile of element with fault current of 4.4 kA

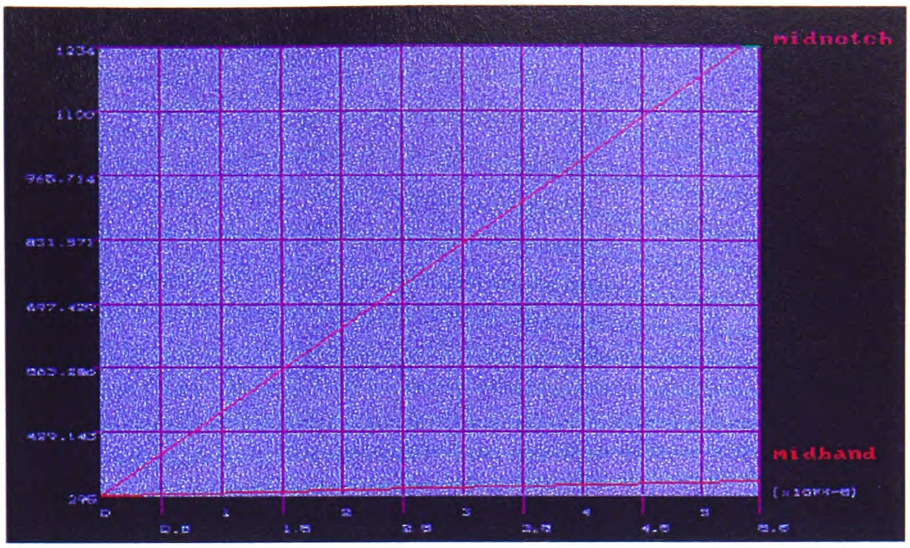


Figure 53 Temperature at centre of notch with fault current of 4.4 kA

If we now consider figures 54 and 55 which show the temperature profile of the silver strip with fault currents of 1.37 kA and 456 A respectively, and compare them with figure 52, you can see that the heat loss from the notch to the main strip starts to have a marked effect on operation as the current decreases.

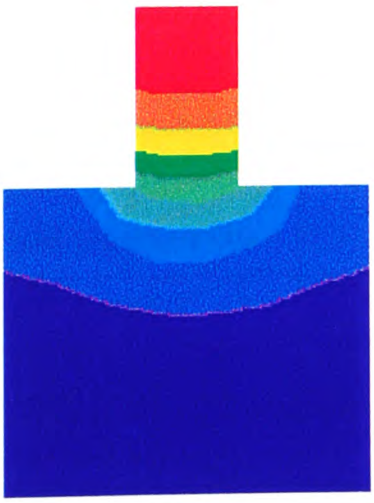


Figure 54 Temperature profile of element with fault current of 1.37 kA

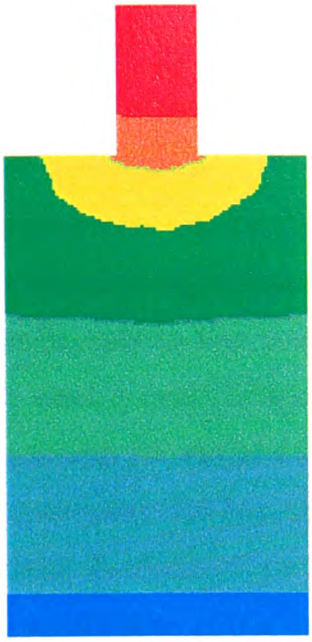


Figure 55 Temperature profile of element with fault current of 456 A

In order to determine when the heat losses to the surrounding medium start to take effect, as well as heat loss to the main strip, a model was produced consisting of the silver strip without the quartz tube.

The same load currents were applied until a marked difference in melting times was observed. The results are shown in table 13.

Ip (kA)	**Time for Notch to Reach 1234 K (s)**	
	Model of Silver Strip and Quartz Tube	**Model of Silver Strip Only**
44	5.3×10^{-7}	5.3×10^{-7}
4.4	5.5×10^{-5}	5.3×10^{-5}
1.37	7.9×10^{-4}	7.2×10^{-4}

Table 13 Comparison of mathematical model results

The results indicate that the heat losses to the surrounding medium start to have a significant effect as the melting times approach 1 ms.

From the original table of results it is seen that the accuracy of the model is drastically diminished for the prospective fault current of 425 A. In this case the model predicted an operating time of 0.037 seconds instead of the correct 0.1 seconds.

The reasons for the large inaccuracies experienced are primarily down to failings of the 2-dimensional model. It would seem reasonable to suggest that at this point heat losses to the surrounding media start to take a much more significant effect. Work has been done to show that when a fuse element is printed onto a quartz substrate, the quartz provides an efficient sink for the heat generated in the restricted (notched) region [24]. By this stage there must also be a significant heat loss from the element to the surrounding sand. Other factors such as neglecting the time that the element material is in a molten state would also have a bearing on the accuracy of the model results. All these effects that play a significant part in the operation of the fuse cannot be accounted for in this type of 2-D model.

7.3.2 Conclusions From Model Results

This first model was of a very crude 2-dimensional nature but was able to give a representation of fuse performance to within ±12% on current for fast operating times, up to approximately 0.03 seconds. For times greater than this, as more heat is lost to the surrounding media, the model would have to be extended to include heat losses to obtain accurate results. However, an indication of when heat loss starts to occur from the notch to the main strip and to the quartz tube was obtained using this model.

The results obtained from this initial modelling indicate that finite element analysis, and the ANSYS package in particular could be successfully utilised to predict pre-arcing fuse operation of Fullran fuses provided a 3-dimensional model of the fuse was produced.

7.4 Areas for Further Investigation and Possible Enhancements to Modelling

Further research work could be carried out on the resistivity of the printed silver strip which would help any further investigation and allow correct definition of material properties. This is an extremely vital property when it comes to modelling as a change in resistivity figure causes vast differences in predicted operating times.

As intimated earlier, the first way to improve the model would be to represent the fuse segment 3-dimensionally including the depth of the quartz tube and the surrounding silica sand. This should give a truer reflection of heat losses and should enable reasonably accurate results to be obtained for longer melting times.

The model could easily be extended / modified to simulate the newly developed multi-element bridge configuration. It would then be possible to predict the region where initial melting transfers from the notches to the bridge. The model could then be used as a design aid to help optimise the dimensions of the element bridge for any new element patterns that are developed incorporating this concept.

It would also be possible to model a number of notches in series and element strips in parallel in order to determine what, if any, affect this has on operation. However, this would involve a large number of nodes / elements which could result in excessively long run times.

8. Summary and Conclusions

This chapter will review firstly the general achievements of the Teaching Company Programme, and then the specific achievements with regards to the development of the Fullran fuse-links.

8.1 Achievements Shown Against Original Development Plan

The following primary objectives which were specified in the original plan of the Teaching Company Programme (shown in chapter 1) were addressed.

a. to increase the company's knowledge and skills in so called 'Fullran' technology using thick-film printing and electroplating techniques.

- A large increase in company knowledge and skills was achieved during the programme.

- A much greater understanding of the Fullran technology was attained through the development of new designs, short circuit testing, analysis of failures etc.

- Element design parameters were pushed to extremes in order to understand their limits, and analysis work was carried out on different substrate materials, silver pastes and grades of silica sand.

b. to introduce new more sophisticated plant and equipment for improved production efficiency and to release existing plant for product development.

- A new silver plating plant was introduced into the production process providing substantial improvement in production efficiency.

- A thorough knowledge of the operation of the plant was obtained during the commissioning period enabling planned maintenance guidelines and the plating plant operating procedures to be drawn up by the author. Further details of these documents are given in appendix A.

c. *to fully investigate the operating characteristics of the 'Fullran' fuse design using mathematical modelling and other simulation techniques.*

- Verification into the suitability of the ANSYS finite element analysis package for modelling of fuse performance was secured.

- An understanding into the effect of when heat losses, both to the main strip and to the surrounding medium, start to have a significant effect on melting times was obtained. Whilst the modelling was not advanced as much as originally hoped, the progress made does provide a firm platform from which to build.

d. *to incorporate this technology in other B & S products to meet new technical standards and thereby consolidate and improve market share in the Electrical Supply Industry.*

- The complete range of DIN dimension 6.3 - 80 A range of fuses were designed, developed and improved to meet relevant and necessary technical standards with regards to their operating characteristics (see section 8.2).

- A totally new concept in element design was conceived and developed by B & S Fuses through the teaching company scheme and introduced into the new designs which used a 'multi-element bridge configuration'. This concept of design has subsequently been patented by Bussmann.

- Investigation into the possibility of transferring the technology into other fuse dimensions was initiated.

- A complete range of 12 kV 6.3 - 63A 2½" British Standard dimension oil fuses, with full range capabilities, was fully certified to IEC 282-1 at the same time as the DIN 6.3 - 40 A range. This range of fuses used a different size quartz tube and had a different construction to the DIN fuses. The fuses were suitable for use under oil and utilised a pyrotechnic striker as used in conventional type oil fuses. Further details are given in Appendix C.

  e. *to improve the company's product quality by establishing new procedures for assessing and improving the new manufacturing processes.*

- New procedures and quality documents were drawn up and put in place upon completion of the commissioning of the new silver plating plant. With the acquisition of B & S Fuses by Bussmann and subsequent relocation of the Fullran manufacturing line, the quality procedures had to be incorporated into the Bussmann quality system. The work that the author had undertaken to update the procedures ensured that the amount of re-work necessary was minimal. Appendix A gives further details of the work carried out on the quality procedures.

  f. *to enable the Associate to gain engineering and management skills to meet the future needs of B & S Fuses.*

- With the assistance of the Teaching Company Management Committee, the author was able to successfully drive the development programme on over the two year period.

- The counsel provided by the industrial and academic supervisors coupled with attendance of relevant seminars and training courses, ensured significant personal and professional development.

- Invaluable experience has been gained in engineering, project management, and product development together with the understanding and application of general business principles and management techniques.

- The 2 year programme was assessed by the Institution of Electrical Engineers, and satisfied in full the requirements of their training regulations. This allows the application for transfer to the class of Members after a further two year period.

  g. to enable the Associate to gain experience in working in a multi-discipline company producing high quality electrical products.

- B & S Fuses being a relatively small company (prior to its acquisition by Bussmann) ensured that useful experience was gained in a variety of disciplines. Indeed, the nature of a small company demands a degree of flexibility in its staff in order to function successfully.

- Experience was secured in a wider range of associated products along with experience of a larger organisational structure upon transfer to the Bussmann site.

8.2 Summary of Improvement in Operating Characteristics

As has been outlined, the major purpose of the programme was the development of the DIN dimension range of fuses to meet relevant and necessary technical standards with regards to their operating characteristics. The shortcomings of the operating characteristics of previous designs were outlined in section 2.6.1. This redesign was a significant piece of work which was, in the main, successfully completed.

Chapters 5 & 6 detailed the development work carried out on the fuse element designs in order to achieve the required modification in the characteristics for the 6.3 - 40 A and 50 - 80 A ranges respectively. The improvements can be best shown by plotting the old and new characteristics on a time / current curve along with the relevant transformer protection operating gates.

Figure 56 shows the old and new operating characteristics of the 40 A designs along with transformer protection operating gates for a 500 kVA transformer.

There are four defined current values / gates from the ESI standard 12-8 [18] shown on the curve. These are:

I_1 This is the minimum acceptable rated current of the fuse-link, i.e. the fuse-link must be capable of running at this current indefinitely without melting.

I_2 This is the magnetising inrush that the fuse-link must withstand at 0.1 seconds. In other words the fuse-link must not operate when subjected to this level of current for 0.1 seconds, for this example the value of current is 275A.

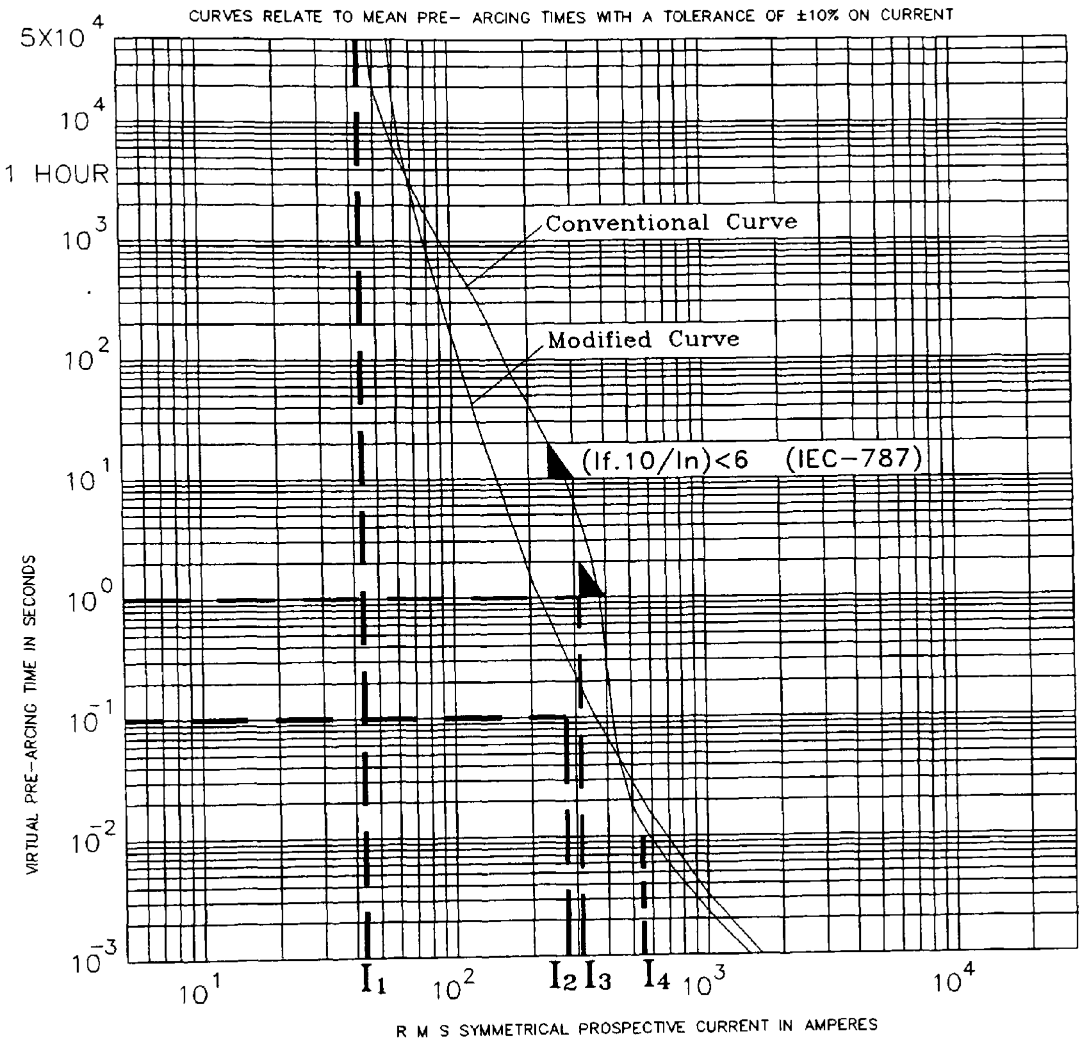
I_3 This is the HV current for a 3-phase fault in the LV terminal zone that must be cleared within 1 second. In this example, the fuse-link must operate within one second for a fault current of 315A.

I_4 This is the maximum HV current at which discrimination with an LV fuse-link is required. In this example, the fuse-link must not operate when subjected to a current of 551A for a time of 0.01 seconds.

The other gate shown on the curve is from IEC-787 [19] and defines the upper limit on pre-arcing current corresponding to 10 seconds. In this example the maximum allowable value of current that causes operation within 10 seconds is 240A.

It can be seen from figure 56, that the prominent 'belly' in the conventional Fullran operating curves has been eliminated with the new element design. This ensures that the new design now operates quickly enough in the 1 second region - i.e. for a 3-phase fault in the terminal zone of the transformer secondary winding. It can also be seen that the new curve also meets all the operating limits set out in ESI 12-8 and IEC-737.

Transformer Protection Operating Gates For a 500 KVA Transformer & The Characteristics of The Conventional And Modified Designs of 40 Amp Fullran Fuses



I_1 — Minimum acceptable rated current of fuse-link.

I_2 — Magnetising inrush current that fuse-link must withstand.

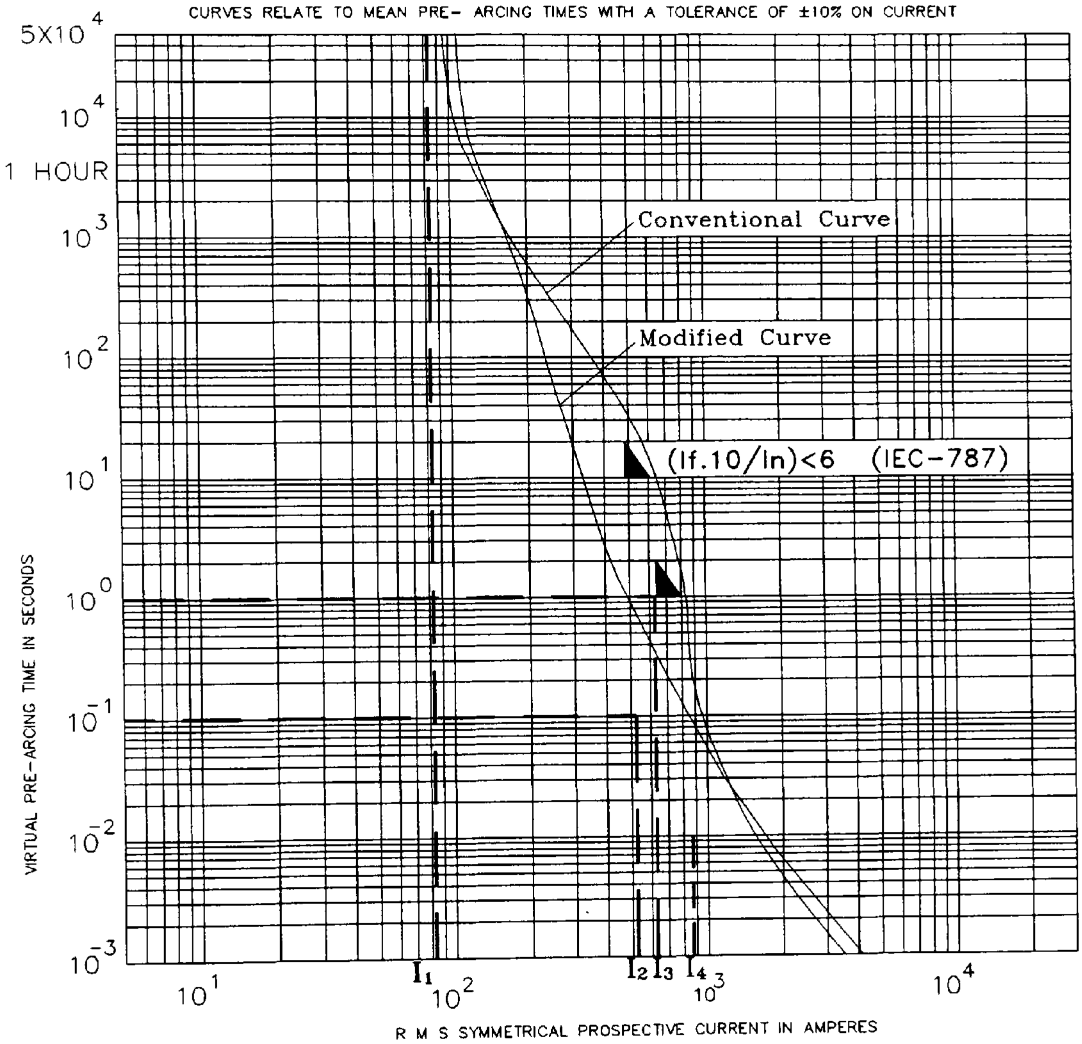
I_3 — H.V. current for 3-phase fault in the l.v. terminal zone that must be cleared within 1 second.

I_4 — Maximum h.v. current at which discrimination with l.v. fuse-link is required.

Figure 56 Transformer protection operating gates for a 500 kVA transformer & the characteristics of the conventional and modified designs of 40 A Fullran fuses

Figure 57 shows the old and new operating characteristics of the 80 A designs along with relevant transformer protection operating gates for a 1000 kVA transformer.

Transformer Protection Operating Gates For a 1000 KVA Transformer & The Characteristics of The Conventional And Modified Designs of 80 Amp Fullran Fuses



I_1 — Minimum acceptable rated current of fuse-link.

I_2 — Magnetising inrush current that fuse-link must withstand.

I_3 — H.V. current for 3-phase fault in the l.v. terminal zone that must be cleared within 1 second.

I_4 — Maximum h.v. current at which discrimination with l.v. fuse-link is required.

Figure 57 Transformer protection operating gates for a 1000 kVA transformer & the characteristics of the conventional and modified designs of 80 A Fullran fuses

Figure 57 shows that the same improvement in operating characteristic has been achieved for the 80 A design as for the 40 A design.

As the complete range of fuses utilised the same element designs, the 'straightening' of the curve was true for the entire series of 6.3 - 80 A fuses. This new characteristic therefore had the effect of enabling all the fuses to meet the transformer application standards laid down for different transformer ratings (as shown in figures 56 & 57). The time current curves relating to the entire range of DIN fuses are shown in Appendix D.

Also shown in Appendix D are the I^2t figures, cut-off characteristics, power loss details and other technical information relating to the complete range of fuses.

8.3 Other Benefits Resulting From the Development Programme

As well as the improvement in the operating characteristics of the fuses, there were other benefits that resulted from the development programme.

The first and obviously welcome bonus to the company was a 20 % reduction in material cost for the 50 and 63 A designs. This cost reduction was due to the new designs using only a single 43 mm quartz tube, thereby saving the significant cost of a 30 mm quartz tube and all the related fittings. This also has another positive effect of a 15 % reduction in manufacturing time for these ratings.

Another aid to manufacture was the fact that only two different element designs are used for the whole series, one for 30 mm tubes and one for 43 mm tubes. (The original Fullran designs used three element designs with a different element pattern being used on the 30 mm tube of the 50 - 80 A fuses). This leads to the obvious advantage of having more common parts for the complete range of fuses.

Finally one other benefit, though less significant, is the reduction the number of M-effect 'tinspots' required per fuse as only one tinspot is required per three elements instead of one per element.

8.4 Summary of the Success of the Teaching Company Programme

The Teaching Company Programme was very successful and proved to be a great benefit to all participating parties. As highlighted in section 8.1, the specific overall objectives of the programme were largely accomplished, namely

- the company's knowledge and skills were greatly increased in the so called 'Fullran' technology using thick-film printing and electroplating techniques.
- new more sophisticated plant and equipment was introduced for improved production efficiency releasing existing plant for product development.
- the operating characteristics of the 'Fullran' fuse design were investigated using finite element analysis modelling techniques.
- the 'Fullran' technology was introduced into other B & S products and met new technical standards.
- new procedures for assessing and improving the new manufacturing processes were established in line with the company's quality policy
- the Associate was able to gain engineering and management skills.
- the Associate gained experience in working in a multi-discipline company producing high quality electrical products.

The company now has a much more comprehensive knowledge of the technical capabilities of this type of fuse design and a complete range of DIN full range fuses with more advantageous operating characteristics is now in production.

The University has been able to cement its links with the fuse industry and has had success in further fuse related project work both at under graduate and post graduate level.

The Associate / author has been able to gain invaluable experience in the design and development of high quality electrical products and secured significant personal and professional development through the programme.

Each Teaching Company Scheme is independently assessed at the end of the programme. The scheme involving the University of Glamorgan and B & S Fuses received a very high grade from the Engineering and Physical Sciences Research Council and was deemed to have produced a 'very significant contribution to the field' and had 'good management and use of resources'.

Appendix A - Fullran Quality and Production Information

During the time of the Teaching Company Scheme, valuable information was obtained on the newly purchased silver plating plant during its commissioning period. Through this, the author was able to draw up a series of plating plant operating guidelines and a maintenance schedule for B & S Fuses which are shown in this appendix.

Also at this time B & S Fuses were moving towards obtaining accreditation to BS 5750, ISO 9002 for the manufacture of High Voltage Fuse-links. The author was charged with the task of updating the existing quality / production procedures for the Fullran fuses, ensuring that they complied with the format of the company's quality manuals and strove towards maintaining and improving the quality of the product produced at B & S Fuses. This appendix also includes a section taken out of the Fullran production procedures and one of the inspection record tables used during the production / inspection process.

Plating Plant Operating Guidelines

Overview of the Plating Process

- The plated tubes are loaded onto the racks in the loading position.
- The transporter moves the rack over the strike tank and dips the tubes in twice.
- The transporter moves the tubes over the plating tank and their resistance is measured.
- The tubes are submerged in the plating solution and a set plating current is passed through the tubes for a set period of time.
- The tubes come up out of the solution and their resistances are measured.
- The PLC calculates the required second current for each position in order for the tubes to reach the set target resistance.

- The tubes are submerged again for a fraction of the first plating time (depending on the factor setting) and are plated at the individually calculated second currents.
- The tubes come up and their final resistance values are measured.
- The transporter moves the tubes over the strike and two rinse tanks in turn, dipping the tubes twice into each tank.
- The finished tubes are unloaded.

Start up Procedure For the Plant

1. Ensure both transporter units are located above a sensor.
2. Slowly open the red handled air valve located behind the plating tank on range A.
3. The jigs should rise up as the air valve is opened. If the transporters move backwards or forwards press the Reset button. If the transporter does not then locate at one of the sensors close off the air valve and seek assistance.
4. Open the red handled air valve fully.
5. Check the level of the Plating Solution - top up if necessary.
6. Switch on the control unit.
7. The circulation pumps should now start pumping.
8. Before using the plant check the temperature of the baths. The temperature can be checked using the temperature control boxes located at the rear of the plating tanks. The tank temperatures should be in the range 22^{o}C - 24^{o}C.
9. If the plating temperature is satisfactory then the calibration procedure can be undertaken, (see calibration procedure). Calibration must be carried out initially on plant start up and also when jigs are changed.
10. Select the operation mode required i.e. 1-5, 6-10, 1-10.
11. Enter the appropriate resistance and time values on the thumbwheel displays. Maximum current should always be 2.0. Note that the time is in increments of ten seconds.

Calibration Procedure

1. Insert five plated tubes with a known resistance of 25 mΩ into the jig.
2. Push Reset button.
3. Using the joystick control (manual mode) move the transporter so that it is above the plating tank.
4. Select the Calibration operation mode.
5. Press the Start button. The tube resistances are read. Any inaccuracies in these measurements will now be accounted for. If any position does not read accurately, press the start button again until 5 good readings are obtained.
6. Using the joystick move the transporter back to the first tank. The plant is now ready for operation.

Altering Time, Time Factor, Resistance and Max Current Settings

The time, time factor, resistance and maximum current settings are set on thumbwheels and are then Entered for the required function.

Time: this is in units of ten seconds i.e. a setting of 2 = 20 seconds. This is the plating time for the initial dip in the process.

Time Factor: this is normally set on 2 and means the second plating dip in the process will last for half the initial dip, 3 would mean one third of the time etc.

Max Current: this is in units of tenths of an ampere i.e. 20 = 2 A. This is the plating current used in the first dip of the process.

Target Resistance: this is in units of tenths of milliohms i.e. 245 = 24.5 mΩ.

Once the required settings have been altered on the thumbwheels, they can be entered for the required function e.g. plating a series of tubes on 1-5, 6-10 or 1-10, or plating tubes on side A or B using the Check Button (see Plating Tubes With Resistance > 400 mΩ).

Plating a Series of Tubes

1. Place the required amount of tubes in the rack(s) and make sure the respective positions are turned on at the control cabinet.
2. Set the selector switch to either 1-5, 6-10, or 1-10 as required.
3. Enter the required values for time etc. via the thumbwheels.
4. Press the start button.

The plating process will now start.

Plating Tubes With Resistance Greater Than 400 mΩ (Check Button Plating)

1. Using the joystick position the tubes over the strike tank and dip in twice.
2. Move the trolley to the plating tank (again using the joystick).
3. For plating on side A choose the 1-5 position on the selector switch, for side B choose position 6-10. Note you can not select 1-10.
4. Set the required plating current and plating time using the relevant thumbwheels.
5. Press the ENTER button.
6. Press the CHECK button.
7. The tubes will come up after the specified time, they can then be manually dipped twice in the strike and rinse tanks, or further plating can be carried out using either an automatic process (if the tubes have been plated to below 400 mΩ) or the check button again.

Running Two Sides Separately

The two sides A and B can be run concurrently with different settings or calibration or 'Check button plating' can be carried out on one side while the other side continues with a 'normal' process. This is done in the following way.

1. Put the selector switch onto 1-5, adjust thumbwheels to required values and press enter.
2. Start the process on side A.
3. Move the selector switch to 6-10, adjust thumbwheels to new values and press enter.
4. Press start or check button as required.

The plant will now run through the process on both sides using the different values. To carry out the calibration on side B whilst A is running, simply select Calibration on the selector switch rather than 6-10 and follow the calibration procedure.

Note: the same applies for starting side B first instead of side A.

Running Both Sides With the Same Settings

To run both sides with the same settings:

1. Put the selector switch onto 1-10, adjust thumbwheels to required values and press enter.
2. Press the two start buttons.

Error Messages

Calculation Error

This occurs between plating dips and is caused by the required second plating current being out of the plating limits i.e. < 0.01 or > 2.5 A.

Note: the tubes will continue to go down into the solution when a calculation error occurs so that if only one position has the error the other four tubes can continue to plate as normal.

The position(s) that have a calculation error on them will flash off and on. At the end of the whole process you can stop the flashing and get rid of the error message by pressing the Reset button.

Measuring Error

This occurs if the tubes being measured have a resistance greater than 400 mΩ, there is no tube in a position that is switched on or if there is a bad contact between the tube and the rack.

If the tubes are greater than 400 mΩ then they can only be plated using the Check button method until they are at a lower resistance.

Fuses not Locked / Unlocked, Side A/B not Up / Down

If any of these messages occur the first thing to check is the air pressure and whether the compressor is switched on. If the air pressure is OK then the most likely cause of fault is a pneumatic switch or solenoid not operating correctly, ask for assistance.

Planned Maintenance / General Housekeeping For New Plant

Daily Checks

1. De-min tank level.
2. Bewt tank level.
3. Heating control box - red light on, MAX MIN displayed and battery OK.
4. Cooler unit on, level OK - via indicator on unit.
5. Temperature of baths.
6. Plating solution levels.
7. Rack contact - during calibration procedure i.e. reading should be 25 3 mΩ.

Tasks

1. When switching plant off locate both trolleys above bath 1 (loading position).

Weekly Checks

1. Calibration tubes accuracies.
2. Health and Safety - cyanide levels in air.
3. Silver build up on racks.

Tasks

1. Swap De-min & Bewt tanks from one side to the other.
2. Take Anode baskets from plating solution for weekends
3. Clean drip trays and cyanide crystals from tanks, control panel etc.
4. General cleaning of work area.

Fortnightly Checks

1. Cyanide & brightener levels.
2. Plate on Bewt tank.

Tasks

1. Fill Amphours / Additions form.
2. Clean Anode bars.

Monthly
Checks

1. Air supply - Pressure (6.2 bar), leaks, oil levels.
2. Impurity levels in rinse tanks & levels of tanks.
3. Condition of silver anodes.

Tasks

1. Trolley contact greasing.
2. Clean air filter.
3. Clean protective screens.

Three Monthly
Checks

1. Pump operation - circulation in tanks.

Tasks

1. Swap pump filter papers.

Six Monthly
Checks

1. Heating and cooling system - operation, levels etc.
2. Wiring and contacts from racks through to terminals in control cabinet.
3. Position sensors - up/down, open/closed.

Tasks

1. Power supply calibration (using calibrated meter). - adjusting for 0.1 & 1 A currents.
2. General scrub down of plant.
3. Calibration of two temperature sensors for each bath.

Fullran Production Procedures

Section 5 Screen Printing

Policy

To establish the correct procedure for the screen printing of fuse element designs onto quartz tubes.

Scope

This procedure shall apply to all screen printed element designs used in the manufacture of Full-Range fuse-links.

Procedure

1. Select the correct printing screen for the required design, using the identification number located on the screen.
2. Position the screen on the relevant printing machine, ensuring correct placement for printing onto the quartz tubes.
3. Prepare the machine for use as follows - activated the mains switch, press the panel switch and connect the compressed air tube.
4. Apply the well stirred paste in front of the feeder and along the printing area.
5. Use a cloth to place the clean quartz tube onto the machine and press the start button.
6. After the machine has completed one full cycle (forward and backward movement) the tube can be carefully removed and placed on the control unit for visual checking with the magnifying glass and fluorescent lamp. (One in five tubes should be checked for printing faults. If a printing fault is experienced the previous four tubes should also be inspected).
7. Store a complete tray of printed tubes in cupboard.
8. Switch off the screen printing machine in reverse order to which it was switched on. (refer to 3.).
9. The squeegee and feeder must be well cleaned with the relevant solvent.
10. All superfluous paste must be removed from the screen before it is cleaned, cleaning is carried out using relevant solvent.

Notes

1. When positioning the screens onto the printing machines the element design should be at least 1 mm from either edge of the tube. A sample set up tube can be utilised to achieve the correct positioning).
2. Ensure that the processing date of the silver paste is within a period of 6 months from the date of manufacture indicated on the container.
3. Printing must be well defined (not spotty) and must be complete.
4. If the printing is bad the tube can be wiped clean using the relevant solvent, and re-used.
5. Three sample tubes of any production batch designated by the Quality Department for measurement (in accordance with in-process inspection schedule) must be taken to the Quality Department for measurement of element parameters.

Important

1. The air ventilation unit must be switched on when carrying out screen printing.
2. The emergency off button is positioned in easy reach of the normal operating position.
3. Latex Gloves must be used at all times when handling the quartz tubes.

B & S Fuses - Fullran Production

Radiographic Inspection Record

Table Ref. FULLQA2

Fuse Description	Rating		No. of Fuses Checked	Reject Quantity	Remarks	Test Date
	kV	A				

Figure 58 Example of an Inspection Record Sheet from Fullran quality procedures

Appendix B - ANSYS Programming Details

The following is a copy of a 'log' programming files used for mathematical modelling using the ANSYS package. (All annotation is prefixed by !)

```
/BATCH
/COM,ANSYS REVISION  5.0        ED     18:58:04    11/06/1994

/FILNAM,mod1_a
/TITLE,Temperature Profile of Fullran 40Amp Element Ip = 44 kA (Mod1_a)
/PREP7
!Read in properties of silver (adjusted for 40 Amp design)
mpread,pracag40,mat
!Read in properties of Quartz for 1.75 mm wall thickness
mpread,sio2_67,mat
!Set analysis to transient type
antype,tran
!Choose Plane67 as element type
et,1,67

!Model
!Determine Keypoints of geometry
k,1,0.975e-3,0
k,2,2.025e-3,0
k,3,2.025e-3,5.45e-3
k,4,2.025e-3,5.975e-3
k,5,1.655e-3,5.975e-3
k,6,1.655e-3,6.5e-3
k,7,1.345e-3,6.5e-3
k,8,1.345e-3,5.975e-3
k,9,0.975e-3,5.975e-3
k,10,0.975e-3,5.45e-3
k,11,0,0
k,12,0,5.975e-3
k,13,0,6.5e-3
k,14,3e-3,0
k,15,3e-3,5.975e-3
k,16,3e-3,6.5e-3

!
!construct area out of keypoints
!
a,1,2,3,10
a,3,4,9,10
a,5,6,7,8
```

```
a,11,1,9,12
a,12,8,7,13
a,2,14,15,4
a,5,15,16,6
aadd,2,3
aplot
/pnum,line,1
lplot
/psymb,defa

!Define number of segments per line for mesh density purposes
LESIZE,1,,,8
LESIZE,2,,,4
LESIZE,3,,,8
LESIZE,4,,,4
LESIZE,5,,,4
LESIZE,7,,,4
LESIZE,8,,,4
LESIZE,9,,,4
LESIZE,10,,,4
LESIZE,26,,,2
LESIZE,28,,,2
LESIZE,12,,,3
LESIZE,13,,,4
LESIZE,14,,,3
LESIZE,15,,,4
LESIZE,16,,,3
LESIZE,17,,,4
LESIZE,18,,,4
LESIZE,19,,,3
LESIZE,20,,,4
LESIZE,21,,,3
LESIZE,22,,,4
LESIZE,23,,,3
LESIZE,24,,,4
LESIZE,25,,,4

!Select material - silver and mesh silver areas
mat,1
amesh,1
amesh,8
!Select material - Quartz and mesh quartz areas
mat,2
amesh,4
amesh,5
amesh,6
amesh,7

!plot out element model
```

```
eplot
save,mod1_a,db
!
!set initial conditions
!Select line1
lsel,s,line,,1
!Select all nodes of selected lines
nsll,s,1
d,all,temp,295
cp,1,volt,all
nsel,all
!Initial load current of virtual zero amperes
f,1,amps,0.0001
lsel,s,line,,9
nsll,s,1
d,all,volt,0
finish
!Enter solution program
/SOLU

nsel,all
/pbc,all,1
nplot
!Set initial time conditions approx to zero
time,1e-10
timint,off
!Apply a step load input
nsubst,1
kbc,1
solve
!Delete temp constraints applied for initial conditions
ddele,all,temp

lsel,s,line,,9
nsll,s,1

nsel,all

! Apply load (fault current)
f,1,amps,2930
!Set time for simulation to run and turn auto time setting on
!Also turn time integration on apply loads and solve
time,1e-6
nsubst,500
autots,on
timint,on
!
kbc,1
solve
```

```
finish
save
/POST1
/edge,1,1
plnsol,temp
finish
/post26
nsol,2,58,temp,,t-mid_not
plvar,2
```

Appendix C - Details of SFGRN Range of Fuse-links

During the time of the Teaching Company Scheme and as part of its programme, a complete range of 12 kV 6.3 - 63 A 2½" British Standard dimension oil fuses (designated SFGRN) with full range capabilities, were fully certified to IEC 282-1. The fuses were designed using the same principles of introducing a multi-element bridge configuration to the element pattern as for the DIN fuses shown in the main body of this dissertation.

This range of fuses used a different size quartz tube and had a different construction to the DIN fuses. The fuses were suitable for use under oil and utilised a pyrotechnic striker as used in conventional type oil fuses.

The design, manufacture and certification of this range of fuses ran concurrently with the development of the DIN range of fuse-links in order to maximise the time in the short-circuit testing stations.

The operating characteristics and design details are given in the following pages.

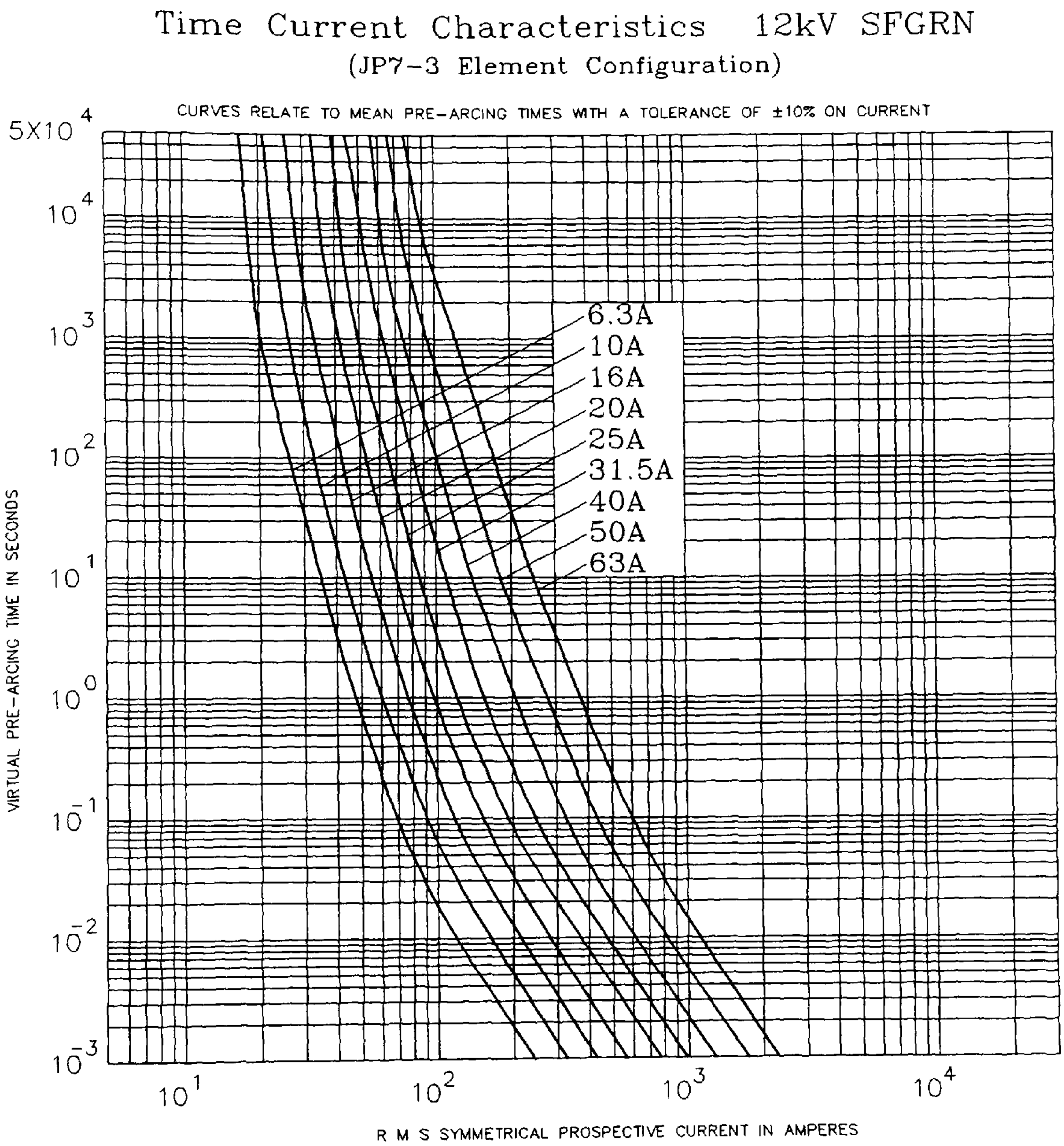


Figure 59 SFGRN operating characteristics

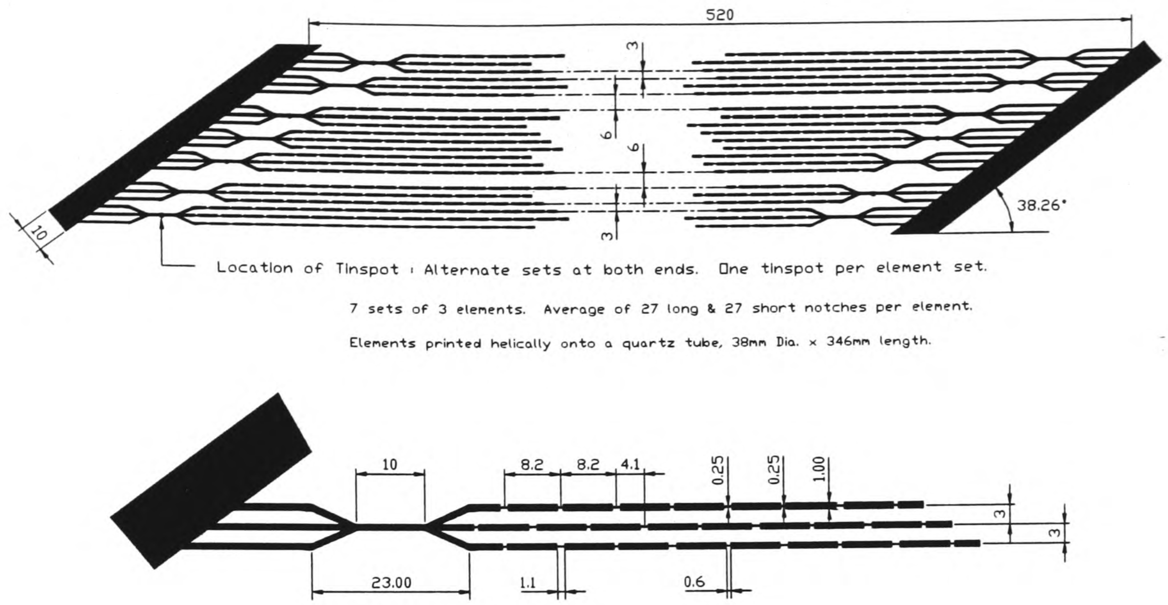
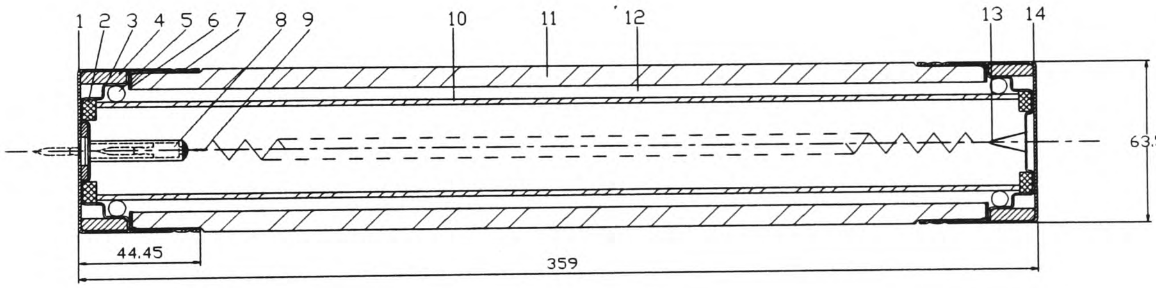


Figure 60 JP7-3 element design details used in SFGRN fuses



	Description	Qty.
1	Outer Cap (Striker End)	1
2	Rubber Washer	2
3	Inner Cap	2
4	Nylon Spacer	2
5	Contact Spring	2
6	PTFE Washer Spacer	2
7	Sealing Ring	2
8	Striker Assembly	1
9	Striker Coil (0.004" Dia. x 630mm)	1
10	Quartz Tube	1
11	Porcelain Barrel	1
12	Silica Sand Filler	To Suit
13	Striker Coil Support	1
14	Outer Cap (Non-Striker End)	1

In	Nominal Res. mΩ
6.3	340
8	243
10	178
12.5	130
16	92
20	67
25	40
31.5	35.5
40	25.5
50	18.5
63	13.5

Figure 61 SFGRN assembly details

Appendix D - Technical Information on Modified Fullran Designs

The following pages contains the technical information on the modified Fullran designs which are now commercially available.

(P)321a : 6.3 - 40 A Range

(P)321b : 50 - 80 A Range

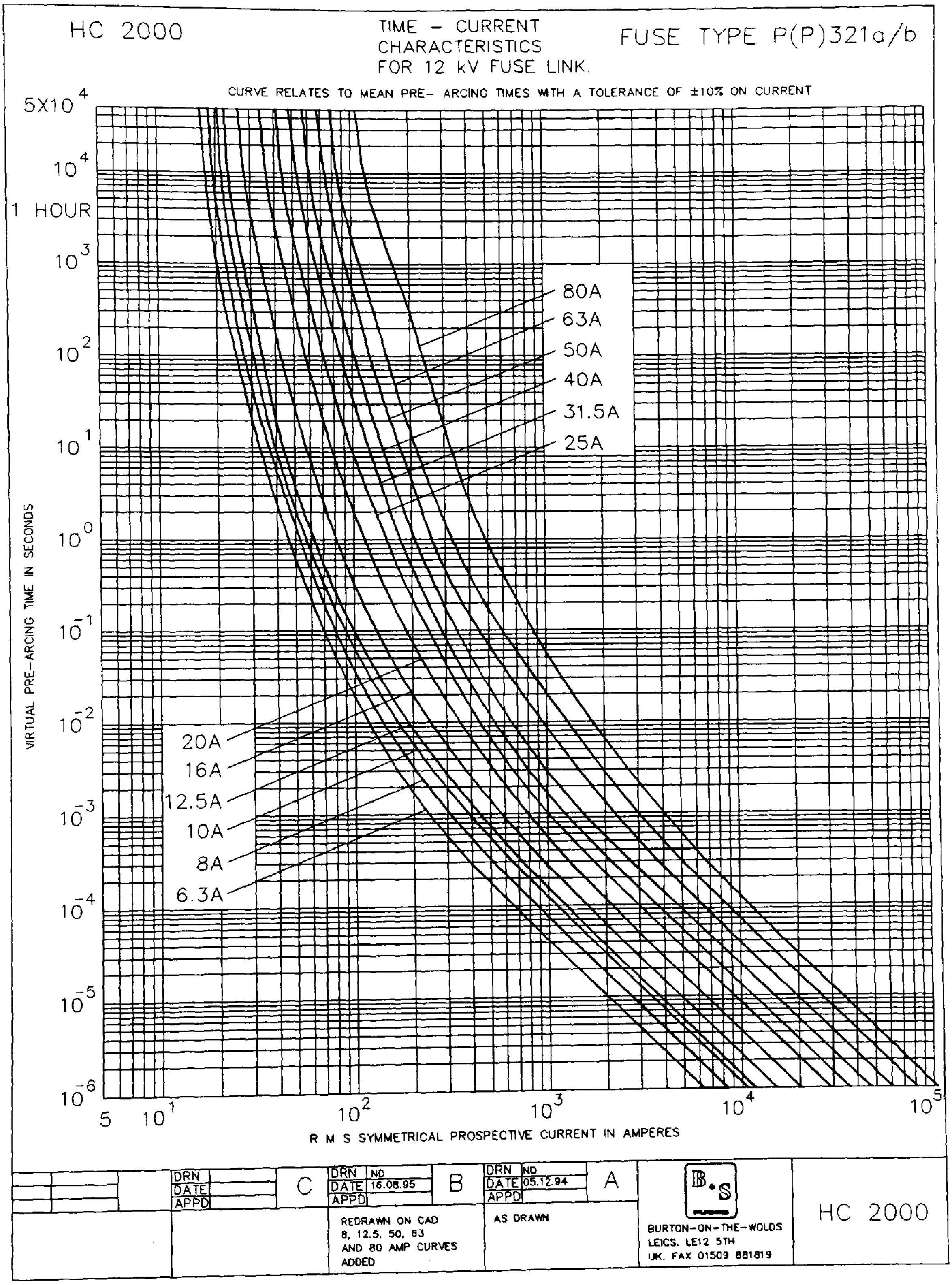


Figure 62 Time/current characteristics of modified Fullran designs

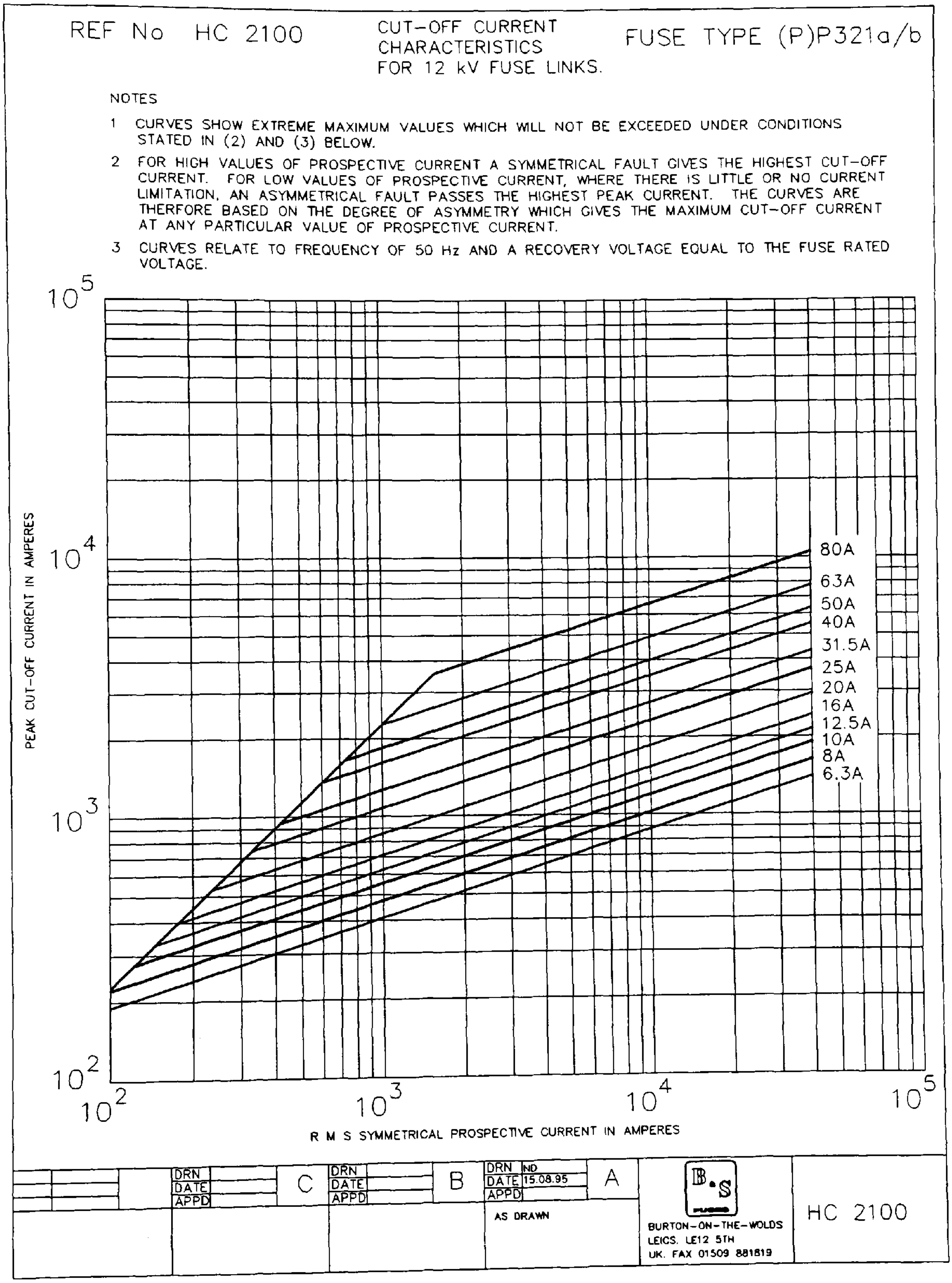


Figure 63 Cut-off characteristics of modified Fullran designs

REF No. HC 2200 **FUSE TYPE (P)P321a/b**

**JOULE INTEGRAL (I^2t) CHARACTERISTICS
FOR 12kV FUSE LINKS**

**Maximum Operating I^2t values relate
to test voltage of 12kV**

FUSE TYPE	CURRENT RATING (AMPS)	MINIMUM PRE-ARCING I^2t ($AMPS^2SEC$)	TOTAL OPERATING I^2t ($AMPS^2SEC$)
PP321a	6.3	3.2 X 10^{1}	1.1 X 10^{2}
PP321a	8	5.7 X 10^{1}	2.0 X 10^{2}
PP321a	10	8.5 X 10^{1}	3.1 X 10^{2}
PP321a	12.5	1.0 X 10^{2}	3.6 X 10^{2}
PP321a	16	1.5 X 10^{2}	6.3 X 10^{2}
PP321a	20	3.4 X 10^{2}	1.7 X 10^{3}
PP321a	25	6.7 X 10^{2}	3.8 X 10^{3}
PP321a	31.5	9.4 X 10^{2}	6.0 X 10^{3}
PP321a	40	1.7 X 10^{3}	1.3 X 10^{4}
PP321b	50	3.1 X 10^{3}	2.6 X 10^{4}
PP321b	63	5.1 X 10^{3}	4.8 X 10^{4}
PP321b	80	1.1 X 10^{4}	9.4 X 10^{4}

			1st issue date 12.10.95 ND	B & S FUSES BURTON-ON-THE-WOLDS LEICS. LE12 5TH UK. FAX 0109 881309

Figure 64 I^2t characteristics of modified Fullran designs

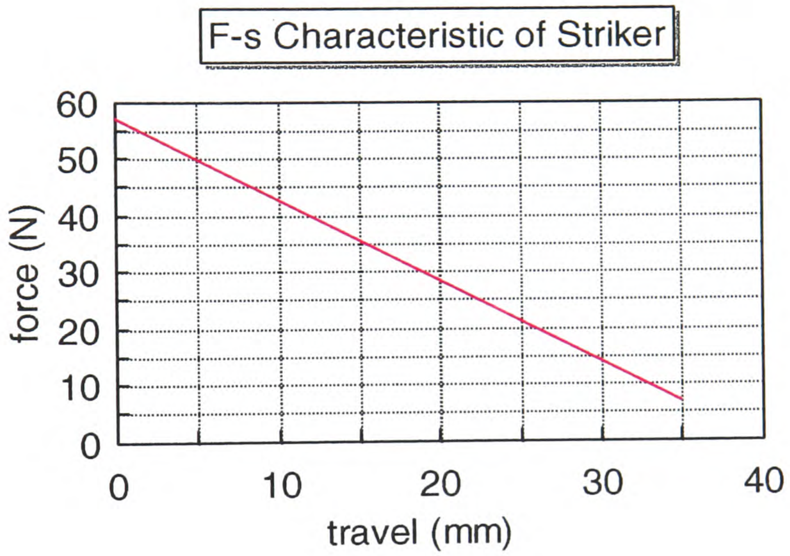
Watts Loss Figures For
Fuse Link Types (P)P321a/b

Current Rating (A)	Nominal Cold Resistance (mΩ)	Nominal Watts Losses	
		@ 50% Rated Current	@ Rated Current
6.3	320	3	14
8	228	4	16
10	167	4	19
12.5	122	5	22
16	87	6	26
20	63	6	29
25	46	8	35
31.5	33	9	40
40	24	10	48
50	18.7	13	61
63	13.5	16	75
80	8.5	14	75

Figure 65 Watts loss data for modified Fullran designs

The Force-Travel (F-s) Characteristic of the Striker

The F-s characteristic of the striker of Fullran fuse-links is in accordance with both DIN 43 625 and IEC 282-1 and is classified as type 'Medium'.



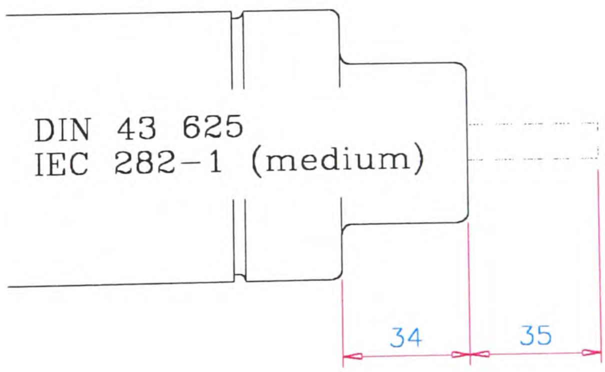


Figure 66 Force travel characteristics of modified Fullran designs

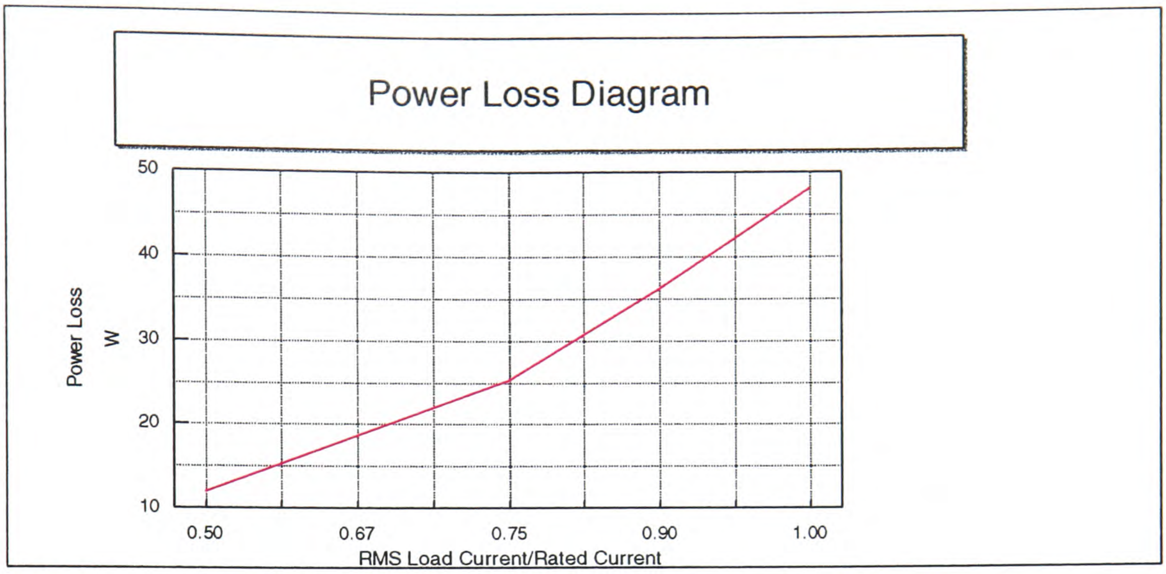


Figure 67 Power loss characteristics of modified 40 Amp Fullran design

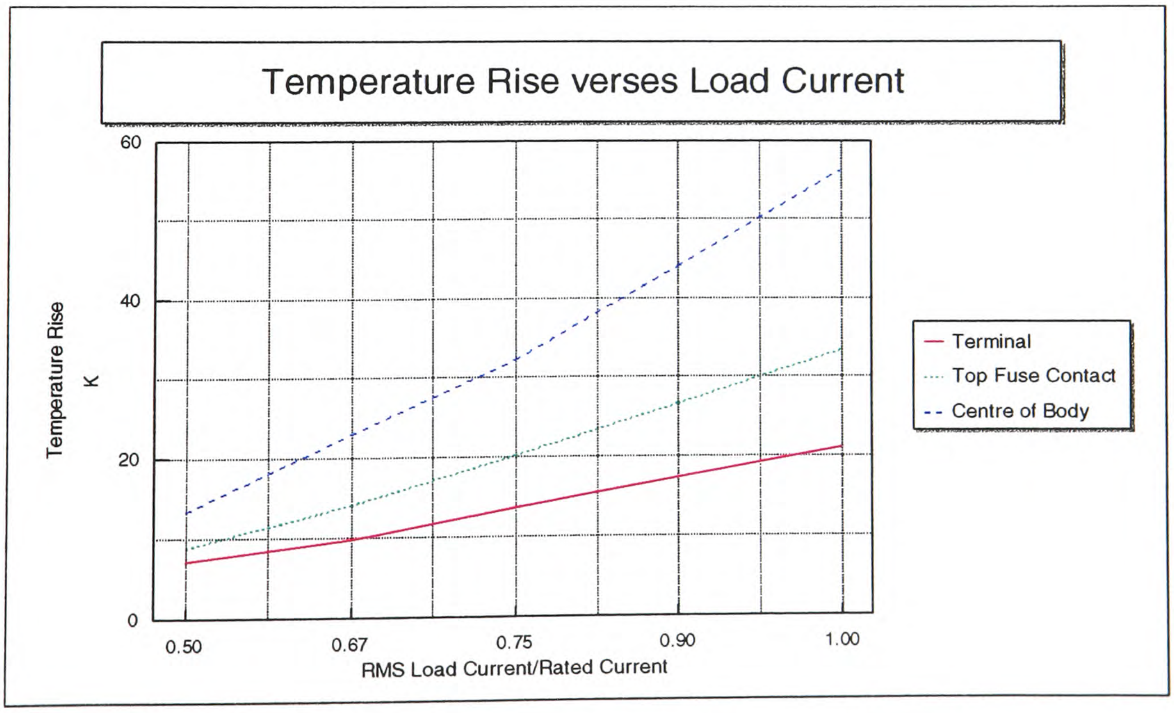


Figure 68 Temperature rise characteristics of modified 40 Amp Fullran design

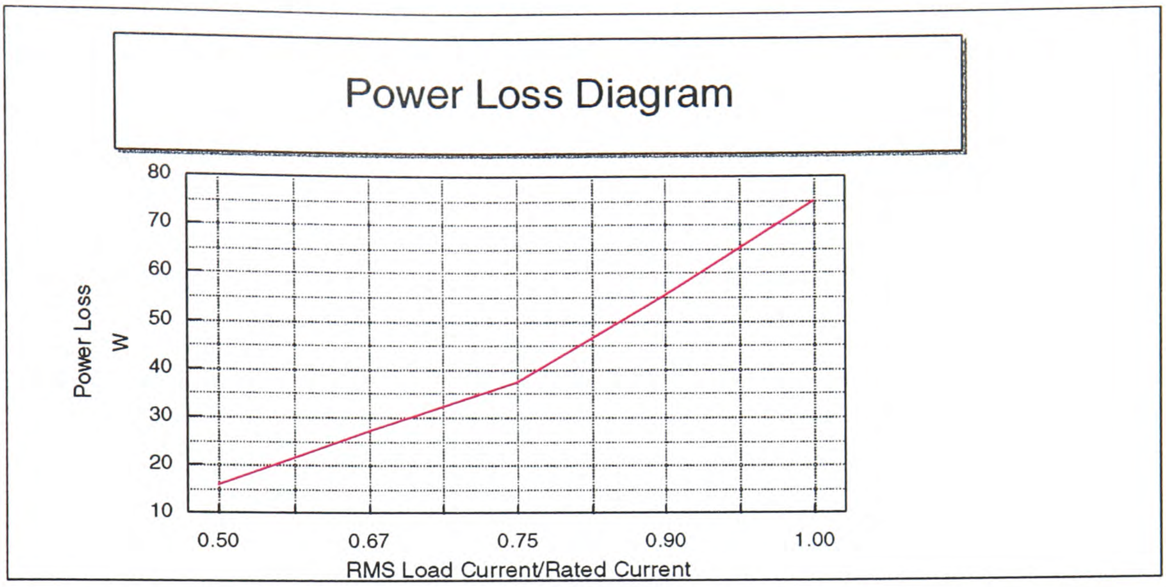


Figure 69 Power loss characteristics of modified 63 Amp Fullran design

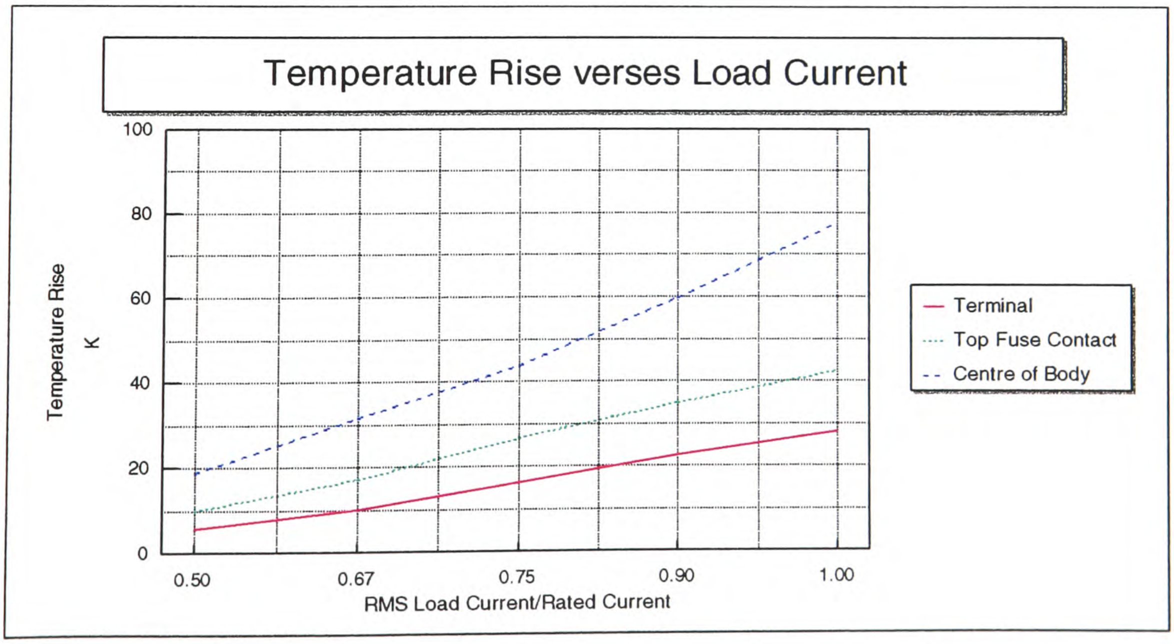


Figure 70 Temperature rise characteristics of modified 63 Amp Fullran design

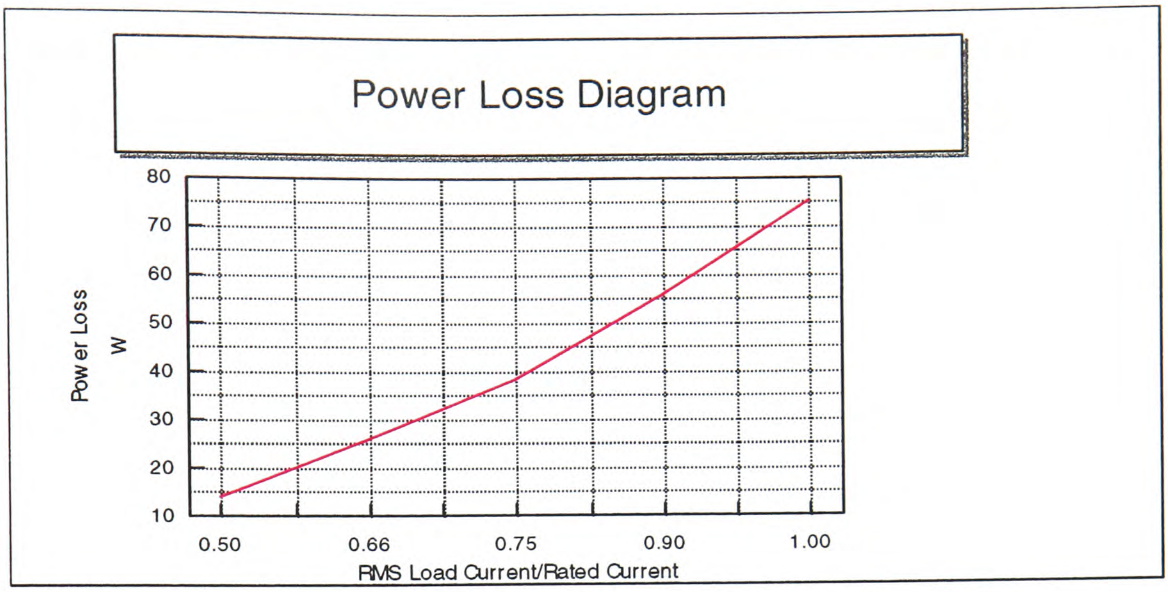


Figure 71 Power loss characteristics of modified 80 Amp Fullran design

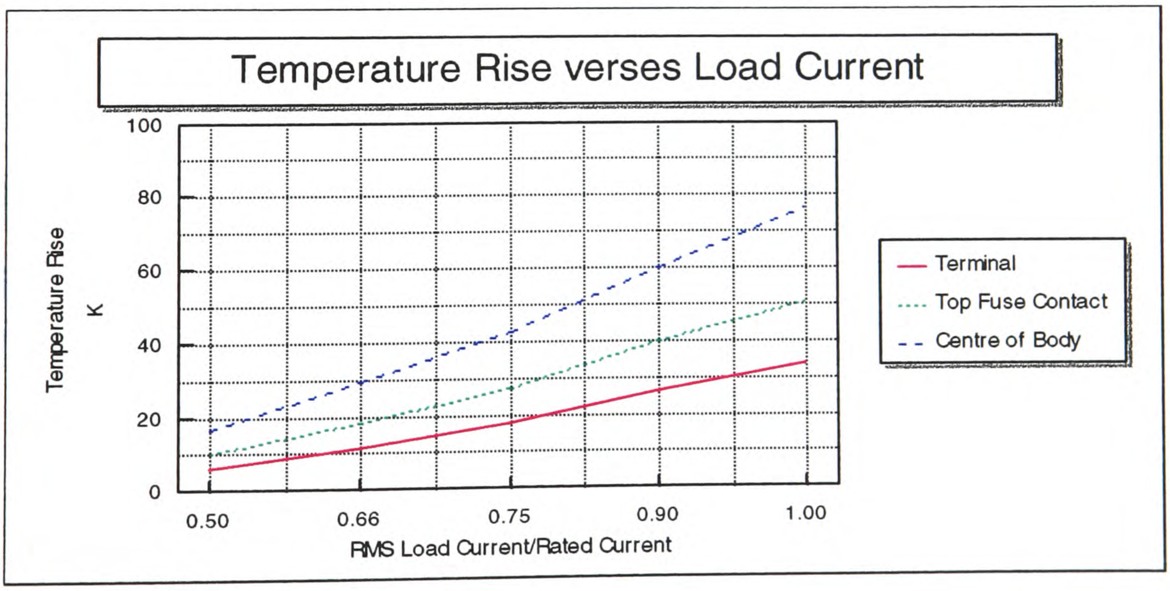


Figure 72 Temperature rise characteristics of modified 80 Amp Fullran design

Glossary

The following is a list of typical terms relating to high voltage fuse-links as originally described in 'Users' Guide to Fuses', H.W. Turner, C. Turner, D.J.A. Williams [6].

Arc energy	The energy produced in the fuse-link during the arcing time.
Arcing angle	The angle on the current wave at which arcing commences.
Arcing I^2t	The I^2t passing through the protected circuit during the arcing time of the fuse.
Arcing time	The interval of time between the instant of the initiation of the arc and the instant of final arc extinction within the fuse.
Arc voltage	The instantaneous value of the voltage which appears across the terminals of a fuse during the arcing time.
Back-up fuse	A fuse which is only able to interrupt currents between a minimum value specified by the manufacturer and the full rated breaking capacity.
Breaking capacity	A value of prospective current that a fuse is capable of breaking at a stated voltage under prescribed conditions of use and behaviour.
BS	British Standard
Closing angle	The angle on the voltage wave at which a circuit is completed.
Critical current	A current within a range of operation of the fuse or other protective device, at which operation is difficult.
Current-limiting fuse-link	A fuse-link that, during and by its operation in a specified current range, limits the current to a substantially lower value than the peak value of the prospective current.

Current rating	The maximum which a fuse will carry continuously, without deterioration and without exceeding a chosen temperature rise under specified conditions.
Cut-off current	The maximum instantaneous value reached by the current during the breaking operation of a fuse-link when it operates in such a manner as to prevent the current from reaching the otherwise attainable maximum.
Cut-off characteristic	A curve giving the cut-off current as a function of the prospective current under stated conditions of operation.
Derating	The reduction in the rating of a fuse, because of the specified conditions under which it is used.
DIN	German Standards Institution. (Deutsche Institut fuer Normung eV)
Element	A part of a fuse-link designed to melt when the fuse operates. The fuse-link may comprise several fuse-elements in parallel.
Expulsion fuse	A type of non-current-limiting high voltage fuse in which gas pressure assists in the extinction of the arc.
Filler	The arc quenching material inside a fuse cartridge.
Fulgurite	The fraction of the filler melted by the arc and subsequently solidified.
Full range fuse	A high voltage fuse-link which will safely interrupt all values of low overcurrent which cause melting of the element(s).
Fuse-link	The part of a fuse including the fuse element, intended to be replaced after the fuse has operated.
Gate	Limiting values (maximum and minimum) within which the characteristics, for example time/current characteristics, shall be contained.
HBC	High breaking capacity (= HRC High rupturing capacity).

HV	High voltage.
High voltage fuse	Fuse designed for use on alternating current system of 50 Hz and 60 Hz and of rated voltages exceeding 1000 V, and/or on dc systems at similar voltage levels.
Homogenous series of fuse-links	A series of fuse-links, within a given size, differing from each other only in such characteristics that for a given test, the testing of one or a reduced number of particular fuse-links of that series may be taken as representative for all the fuse-links of the series itself.
IEC	International Electrotechnical Commission.
ISO	International Standards Organisation.
I^2t	(Joule integral) The integral of the square of the current over a given time. The units are amp^{2}seconds.
I^2t characteristic	A curve giving I^2t values (pre-arcing I^2t and/or total operating I^2t) as a function of prospective current under stated conditions of operation. Alternatively: A graph or diagram showing minimum prearcing I^2t and maximum total operating I^2t as a function of rated current.
KEMA	The Netherlands Testing Authority (NV tot Keuring van Elektrotechnische Materialen).
LV	Low voltage.
Let-through energy	The energy let through to the protected circuit during fuse operation.
Let-through I^2t	The I^2t passing through the protected circuit during fuse operating time. (= total operating I^2t).
Making angle	The angle on the voltage wave at which the circuit is connected to the supply.

M-effect	The deposition of a low melting point metal on a fuse element, having the effect of dissolving the underlying fuse-element metal at small overcurrents.
Melting time	The time between commencement of a current large enough to cause the fuse element to melt and the instant when its smallest cross section is molten.
Minimum breaking current (I_{mbc})	The minimum current which the fuse can be guaranteed to disconnect satisfactorily.
Minimum melting current (I_{mmc})	The minimum current which will cause the fuse element to melt under specified conditions.
Non current-limiting fuse	A fuse-link that during its operation in a specified current range does not limit the current, so that the current continues to rise towards the peak value of the prospective current.
Operation (of a fuse)	Melting of the fuse element, resulting in the satisfactory interruption of a fault current in a circuit protected by the fuse.
Operating time	(Total clearing time) The sum of the pre-arcing and the arcing time.
Overcurrent	Any current above the rated current of a fuse-link. (Often used for small multiples of the rated current).
Peak let-through current	The peak current, let-through by the fuse when operating on high prospective current. For a current-limiting fuse this is synonymous with cut-off current.
Power dissipation of a fuse-link	The power released in a fuse-link carrying rated current under specified conditions.
Pre-arcing I^2t	The I^2t passing through the protected circuit during fuse pre-arcing time.

Pre-arcing time	The time between the commencement of a current large enough to cause the fuse element to melt and the instant when the arc is initiated.
Prospective current	(Available current) The current that would flow in the circuit, if the fuse were replaced by a conductor of negligible impedance.
R10 series	A logarithmic scale of numbers, obtained by dividing each decade into ten equal logarithmic steps, which are the rounded up or down to produce not more than three significant figures e.g.. for 2 decades: 10, 12, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 120, 160, 200, 250, 315, 400, 500, 630, 800, 1000.
Recovery voltage	The voltage which appears across the terminals of a fuse after breaking of the current.
Striker	A mechanical device forming part of a fuse-link which, when the fuse operates, releases the energy required to cause operation of other apparatus or indicators.
Time/current characteristic	A curve giving pre-arcing time or operating time as a function of the prospective current under stated conditions of operation. (For times longer than 0.1 seconds for practical purposes the difference between pre-arcing and operating time is negligible).
Total operating I^2t	The I^2t flowing in the protected circuit during the operating time of the fuse.
Virtual time	The value of I^2t divided by the square of the corresponding prospective current.
Voltage rating	The voltage for which the fuse is designed.
Watts loss (of fuses)	see 'Power dissipation'.

References

[1] KAUFMANN, M., JARRETT, G.S.H. : 'Power System Protection Vol 1. Principles and Components'. Chapter 1 'Role of Protection'. Electricity Council, Peter Peregrinus, 1981

[2] SAY, M.G. : 'Electrical Engineer's Reference Book, 13th Edition'. Butterworth, London, 1973

[3] TURNER, H.W., TURNER, C. : 'Power System Protection Vol 1. Principles and Components'. Chapter 5 'Fuses'. Electricity Council, Peter Peregrinus, 1981

[4] British Standards Institution. 'BS88 Cartridge Fuses for Voltages up to and Including 1000 V a.c. and 15 V d.c. Part 1: 1988 Specification of General Requirements'.

[5] International Electrotechnical Commission. IEC 282-1 (1994) 'High-Voltage Fuses. Part 1: Current Limiting Fuses'.

[6] TURNER, H.W., TURNER, C, WILLIAMS, D.J.A. : 'User's Guide to Fuses'. ERA Report No. 87-0186R. ERA Technology 1987

[7] JACKS, E. : 'High Rupturing Capacity Fuses Design and Application for Safety in Electrical Systems'. E. & F. N. Spon, London, 1975

[8] WRIGHT, A, NEWBERY, P.G. : 'Electric Fuses'. Peter Peregrinus, 1982

[9] HOEKEMA, G.R. : 'Report on the Meeting of IEC 32A High Voltage Fuses'. Elektrotechniek, Netherlands, 64, 1, 1986, 17-18.

[10] ROSEN, P. : 'The Low Overcurrent Breaking Performance of High Voltage Current Limiting Fuses'. Fourth International Symposium on Arc Switching Phenomena. Lodz, Poland, 1981.

[11] PRIME, J. : Private Communication.

[12] ROSEN, P.: 'Full-Range Fusing' - A New Concept in System Protection. Electrical Review, 22/29, 1983

[13] ROSEN, P, NEWBERY, P.G. : 'Recent Advances in HRC Fuse Technology'. Electronics and Power, June 1983

[14] Holec Systemen en Componenten B.V. Technical Publication Number 22.7.2. 'HV Fuse-Links Type Fullran'

[15] METCALF, A.W. : 'A New Fuse Phenomena". BEAMA Journal, 1939, 44 pp. 109-12 and 151-2.

[16] BEAUJEAN, D.A., NEWBERY, P.G., AND JAYNE, M.G. : 'Long-Time Operation of High Breaking Capacity Fuses', IEE Proc., 1993, 140, (4), pp. 331-337

[17] EDWARDS, J. : 'Electroplating - A Guide for Designers and Engineers'. Committee for the Promotion of Electroplating, 1983.

[18] Electricity Supply Industry. Standard 12-8. 'The Application of Fuse-Links to 11 kV/415 V and 6.6 kV/415 V Underground Distribution Networks'. Issue 2 October 1986.

[19] International Electrotechnical Commission. IEC 787 (1983). Application Guide for the Selection of Fuse-Links of High Voltage Fuses for Transformer Circuit Applications.

[20] ROSEN, P., GIBSON, J.W. : 'HV Fuses for Transformers - UK Practice'. Electrical Times, February 1979

[21] ROSEN, P. : 'Fuse is Adaptable to New Load-Break Designs'. Electrical Review, October 1981

[22] CLARKE, G.J., ROSEN, P. : 'The Ring Disconnecting Unit with Full Range Fuses - A New Concept in System Protection'. CIRED, Luik, Belgium, 1987. E16/1-6

[23] LEACH, J.G., NEWBERY, P.G., AND WRIGHT, A. : 'Analysis of High-Rupturing-Capacity Fuselink Prearcing Phenomena by a Finite-Difference Method', IEE Proc., 1973, 120, (9), pp. 987-993

[24] de COGAN, D., HOWE, A.F. and WEBB, P.W. : 'Temperature Measurements of Thin Films on Substrates', IEE Proceedings, Vol. 132, Pt.1, No.3, June1985

[25] MIKULECKY, H.W. : 'Current Limiting Fuse Arc Voltage Characteristics'. IEEE Proc, 1967, pp. 67-43

[26] BAXTER, H.W., CREE, M.T. : 'The Influence of Circuit Constants and Fuse Design on the A.C. Arc Re-Ignition Voltage of Cartridge Fuses'. The British Electrical and Allied Industries Research Association, Technical Report G/T228, 1951

[27] PASTOR, Yu.A. : 'The Dependence of the Arc Extinction Characteristics of Fuses on the Number and Shape of Incisions in the Fusible Element'. Teknicheskikh Nauk, 1969, pp. 57-61

[28] POWELL, A.H., SCHUCK, C.L. : 'Ribbon Elements for High Voltage Current Limiting Fuses'. AIEE Transactions (Power Apparatus and Systems), vol. 74, 1955, pp. 635-643

[29] BAXTER, H.W., GALANIDES, A.R. : 'The Effect of Filler Deficiency on the Performance of Cartridge Fuses'. The Electrical Research Association, Technical Report G/T308, 1958

[30] CHICKEN, W.J. : 'High Voltage Powder-Filled Fuse-Links for Power Distribution Circuits'. Electrical Review, April 1964

[31] BAXTER, H.W. : 'Fundamental Study of the Performance of Cartridge Fuses in A.C. Circuits'. The British Electrical and Allied Industries Research Association, Technical Report G/T198, 1947

[32] WILKINS, R., and McEWAN, P.M. : 'AC Short Circuit Performance of Notched Fuse Elements'. IEE Proc., 1975, 122, (3), pp. 288-292

[33] XIAN-ZHONG, and JI-MEI : 'The Simulation of Pre-Arcing Characteristics of Fuse Elements in the Finite Element Method'. Proc. 3rd International Conference on Electric Fuses and their Applications, Eindhoven, The Netherlands, May 1987, pp. 24-29

[34] BEAUJEAN, D.A. : 'Modelling the M-effect in H.R.C. fuses'. PhD Thesis, Polytechnic of Wales, March 1991

[35] SLOOT, J.G.J. : 'Analog Simulations of the Heat Flow in a High Voltage Fuse'. Proc. 4th International Conference on Electric Fuses and their Applications, Nottingham, U.K., 1991

[36] Swanson Analysis Systems. 'ANSYS User's Manual Revision 5.0 Volume I Procedures'

[37] GIBSON, J.W. : 'The High-Rupturing-Capacity Cartridge Fuse, With Special Reference to Short circuit Performance', J.IEE, 1941, 88, Pt.1, pp.132-135